Technical Note 4-87

HUMAN ENGINEERING LABORATORY GROUNDING ANALYSIS (HELGA)-II

Walter N. McJilton
Human Engineering Laboratory

Charles R. Beek
CALCULON Corporation
1301 Piccard Drive
Rockville, MD 20850

July 1987
AMCMS Code 612716.H700011

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U. S. ARMY HUMAN ENGINEERING LABORATORY

Aberdeen Proving Ground, Maryland

SECURITY CLASSIFICATION OF THIS PAGE

AD-A185 367

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp. Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
Technical Note 4-87

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
CALCULON Corporation

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
1301 Piccard Drive
Rockville, MD 20850

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
Human Engineering Laboratory

8b. OFFICE SYMBOL *(If applicable)*
SLCHE

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
DAAK11-84-D-0008

8c. ADDRESS *(City, State, and ZIP Code)*
Aberdeen Proving Ground, MD 21005-5001

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO
6.27.16.A	1L162716AH70		

11. TITLE *(Include Security Classification)*
Human Engineering Laboratory Grounding Analysis (HELGA)-II

12. PERSONAL AUTHOR(S) Walter N. McJilton
Charles R. Beek

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Final	FROM ________ TO ________	July 1987	73

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
13	12	
09	01	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Earth grounding; Grounding techniques; Ground resistivity; Grounding rods; Grounding

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report documents the development of an alternate earth grounding technique for tactical applications, specifically to correct the human factors issues associated with the 6-foot ground rod currently in wide use throughout the Army. Three alternate grounding systems were identified and tested at several field sites that represented a broad variety of environments. The three alternate designs tested were copper screen mats, horizontal surface wire with ground pegs, and horizontal buried wire.

(see reverse side)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED XX SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Doris S. Eanes

22b. TELEPHONE *(Include Area Code)*
301-278-4478

22c. OFFICE SYMBOL
SLCHE-SS-TS

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

19. Contd

The results showed that the surface wire configuration is the best overall design. The study also indicated that

The performance of installed ground systems and potential grounding sites should be measured. A null-balance earth tester would serve that purpose.

The Army should publish revised guidance on tactical grounding practices.

AMCMS Code 612716.H700011 | Technical Note 4-87

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Walter N. McJilton
Human Engineering Laboratory

Charles R. Beek
CALCULON Corporation
1301 Piccard Drive
Rockville, MD 20850

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APPROVED: John D. Weisz
JOHN D. WEISZ
Director
Human Engineering Laboratory

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Aberdeen Proving Ground, Maryland 21005-5001

FOREWORD

Following the completion of the study described in this document, the surface wire grounding system (SWGS) underwent some further design refinement. The refinement process was completed and accepted for fielding action by CECOM (Communications-Electronics Command) in May 1987.

In the final design the following changes were made:

1. the wire length was reduced to 70 feet;

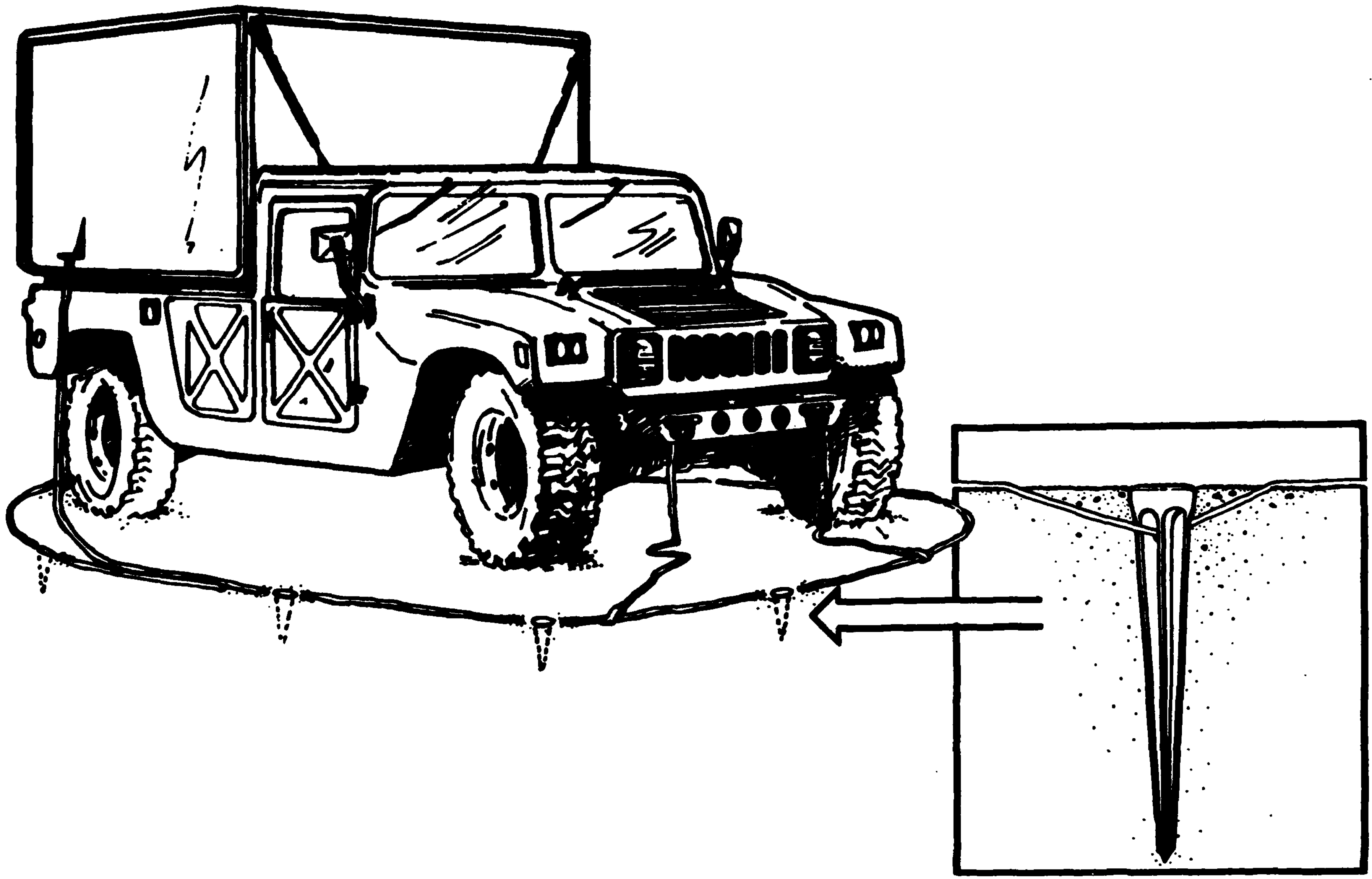
2. three short wires (approximately 6 feet) with quick-connect fasteners at each end were added to connect the SWGS to three additional points on the equipment being grounded;

3. a tapered peg was used to improve soil contact and make removal easier;

4. the number of pegs was reduced to 15; and

5. the length of the pegs was increased to 10 inches.

To improve lightning protection potential, the method of installation of the SWGS has been changed to a loop around the equipment as shown in the figure on the opposite page, instead of in a straight line as discussed in this report.



Current Surface Wire Grounding System Design

ACKNOWLEDGMENT

This report was prepared by CALCULON Corporation under Contract No. DAAK11-84-D-0008, for the Human Engineering Laboratory (HEL), at Aberdeen Proving Ground, Maryland. It documents a study performed by HEL under the direction of Mr. Russell M. Phelps, Communications-Electronics Team Leader. The principal investigator for HEL was Mr. Walter N. McJilton. The principal advisor to the project was Dr. Bernhard Keiser, Keiser Engineering, Inc.

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EXECUTIVE SUMMARY

The increased use of computers and other low-current equipment by tactical units has prompted a review of existing Army grounding practices. This equipment is very sensitive to transient power surges, electrical noise, and stray currents. The negative impact of these conditions can be reduced with effective grounding.

Current Army doctrine for tactical units, emphasizing speed and movement, has also prompted the need to consider new grounding practices. Communications-electronic (CE) facilities often must be set up, operated, and removed in a few hours or a few days at most. Grounding systems must therefore be quick, easy to install, and easy to remove. Traditional Army practice is to use vertical ground rods that are typically 6 feet long, weigh 10 pounds, and are driven into the ground with a 10-pound sledge hammer. This can be hazardous or difficult, depending on terrain and weather conditions.

The Human Engineering Laboratory (HEL) at Aberdeen Proving Ground, Maryland, early in 1983, initiated a study (named HELGA) developing alternative earth-grounding techniques and identifying methods for testing new grounding equipment. In 1984, HEL followed up with the HELGA-II project to experimentally evaluate evolving concepts from the earlier study and to further develop and test new grounding techniques. Three alternative grounding systems were field-tested and evaluated against a standard 6-foot ground rod:

- Copper screen mats
- Horizontal surface wire with ground pegs
- Horizontal buried wire

The two primary measurements used for the evaluation were the grounding system resistance and the soil resistivity (a measure of the resistance of the soil at a particular grounding site to the flow of electrical current from the grounding system). In addition, measurements were also made of the weights, the dimensions related to handling and storage, and the times to install and remove the grounding systems. Baseline comparative data were collected at the following field sites, representing a broad variety of tactical environments:

- Aberdeen Proving Ground, Maryland
- Fort Drum, New York
- Fort Bliss, Texas
- Yakima Firing Center, Washington
- Fort Lewis, Washington
- Fort Story, Virginia
- Fort Huachuca, Arizona

The data obtained during these field tests showed that, for these particular sites, 100 feet of surface wire with 26 ground pegs (6 inches long) generally provided from 20 to 90 percent lower resistance values than a single 6-foot ground rod. The weight, storage parameters, and times to install and remove were roughly similar for the surface wire with pegs and the ground rod. Surface wire with ground pegs was found to be adaptable for installation at all of the test sites; however, there were several cases when the ground rod could not be installed because of the presence of rock or hard soil. It was safer and easier to use a 3-pound hand-held hammer to install the surface wire with pegs rather than the 10-pound sledge hammer required for the ground rod.

The buried wire generally gave a superior performance to the ground rod when firmly embedded in the soil. This configuration, however, includes a special plow and wire spool designed to be attached to the rear bumper of a 2-1/2-ton truck for trenching and laying of the wire. Its system weight is the highest of all configurations tested, and storage and handling factors are also more burdensome than with the ground rod.

The mats' grounding performance varied widely depending on the degree of contact with the soil. It was difficult to firmly embed the mats over grass, rocks, and rough terrain.

The null-balance earth tester, TS-3221/U, was found to be a valuable tool for measuring grounding system resistance and soil resistivity. It provided a means for prospecting for good grounding sites and selecting the best type of grounding configuration to use at a particular site. It was simple to use and the procedures were easily learned by local enlisted personnel.

The following recommendations are based on the results of the field tests:

- The Army use surface wire with ground pegs as a superior alternative to ground rods for grounding tactical mobile CE equipment.
- The Army use a null-balance earth tester for prospecting grounding sites and measuring performance of installed grounding systems.
- The Army publish a revised guidance document on grounding practices, including the use of horizontal earth-electrode systems, such as the surface wire with ground pegs, and the use of a null-balance earth tester.

HUMAN ENGINEERING LABORATORY GROUNDING ANALYSIS (HELGA)-II

INTRODUCTION

The increased use of computers and other low-current systems by tactical units has prompted a review of existing Army grounding practices. The new automatic circuit and message switches (e.g., AN/TTC-39 and AN/TYC-39 switches) that are currently being deployed throughout the United States, NATO, and the Pacific arenas are examples of such low-current systems. They use embedded processors and maintain extensive data bases that are very sensitive to transient power surges, electrical noise, and stray currents. The negative impact of these conditions, however, can be reduced with effective grounding.

Current Army doctrine emphasizes speed and movement for tactical units. Mobile or transportable tactical systems often encounter special situations that require alternatives to the usual practice of driving ground rods into the soil. Because of the temporary nature of the site, communications-electronic (CE) facilities often must be set up, operated, and removed in a few hours or a few days at most. Soil conditions may vary from site to site, requiring a simple method of site surveying and then using the most appropriate earth-electrode system.

Traditional Army guidance calls for the use of one or more vertical ground rods driven into the soil. Most tactical units do not routinely measure the effectiveness of such grounding systems, nor are they knowledgeable about the procedures for doing so. Further, they normally do not "prospect" for good grounding sites. In some situations, it is difficult if not impossible to install ground rods because of the type of terrain (bedrock or other hard soil condition below the surface). In such cases, it is also difficult to remove the ground rods, requiring several spare rods to be carried on field operations. Once a ground rod has been installed, it is impossible to verify if the rod has been shortened (i.e., the practice of "cheating" on grounding potential to make installation and removal easier). Also, trying to strike a ground rod that is about 6 feet above the ground, using a 10-pound sledge hammer, is difficult as well as hazardous.

In 1983, the Human Engineering Laboratory (HEL), at Aberdeen Proving Ground, Maryland, initiated a study to identify alternative earth-grounding techniques that might reduce some of the human factors issues and determine an acceptable method for testing these techniques (Keiser, 1984). Keiser recommended the Army use copper mats and/or horizontal buried wire as alternatives to the vertical ground rod. He also suggested the use of a null-balance earth tester (commonly called a Megger®) for testing the effectiveness of grounding equipment. HEL then initiated the HELGA-II project to experimentally evaluate the evolving concepts from the Keiser study and to further develop and test new grounding techniques. The results are presented in this report.

OBJECTIVES

The Human Engineering Laboratory Grounding Analysis (HELGA)-II project was established with the following objectives:

- To evaluate current procedures and practices for grounding mobile or transportable CE systems and to determine where improvement or corrective action is warranted.
- To evaluate alternative grounding techniques for improved human performance.

METHOD

Participants

The participants in this study were personnel from HEL, contractor support, and on-site military personnel at various Army posts.

Apparatus

Electrical current and resistance measurements were taken on various earth-electrode systems using a multimeter and/or a null-balance earth tester, TS-3221/U. This test set, commonly called by its trade name, Megger®, measures ground resistance of earth electrodes.

The test electrodes and probes used with the null-balance earth test set during this study are 1/2-inch brass rods, 18 inches long. The leads used with these rods are #12 copper wire connected by hose clamps.

Procedure

This study was conducted in three phases. First, exploratory development was carried out at Aberdeen Proving Ground (APG), Maryland. It was designed to refine and develop alternate grounding techniques identified in the initial HELGA effort conducted by Dr. Keiser. Upon completion of the exploratory work, a second phase, to field-test and evaluate the alternative grounding systems versus the standard ground rod was begun. The results of the second phase failed to produce earth-electrode system-resistance measurements that would provide acceptable grounding conditions. Therefore, a third phase was initiated to identify techniques for enhancing grounding performance.

Phase I - Exploratory Development

Initial testing took place on APG using the standard Army 6-foot long, 3/4-inch-diameter, galvanized steel ground rod (see Figure 1). Use of this rod was considered representative of current Army tactical unit grounding procedures for CE systems. The rod was driven all the way into the ground using a 10-pound sledge hammer.

As an alternative grounding device, copper screen mats were made based on a recommendation by Keiser (1984). Each mat was 6 feet by 8.2 feet, made in the APG shops out of 1/4-inch wide flat copper wire braid woven into a diamond mesh pattern, having 3-inch spacings (see Figure 2). The surface area of one side of each mat was 1,234 square inches. Two mats were connected by 50 feet of 1/4-inch copper braid and weighed approximately 8 pounds.

Because of an observed need to better anchor the mats to the soil, steel ground pegs were designed and made in the APG shops. Four pegs were used with each mat to anchor the corners of the mats. Steel pegs of 1/2-inch diameters and 6-, 16-, and 18-inch lengths were used at different times to anchor the mats. In addition, sandbags and/or cement blocks were sometimes placed on the mats to keep them in close contact with the earth.

Two types of horizontal wire grounding systems were also tested--the buried and surface wire systems. These two horizontal systems evolved into a 3/4-inch wide flat copper braid tape and was initially used as an alternative to the copper screen mats (see Figure 3). Subsequently, various diameters and lengths of stranded steel wire cable were tested as horizontal surface earth electrodes. The diameters of wire tested were 3/32", 1/8", 3/16", and 1/4". Wire lengths varied from 30 feet to 200 feet.

Galvanized steel ground pegs of 1/2-inch-diameter and in 6-, 12-, and 16-inch lengths were used in groups, connected together by steel surface wire or copper braid. These ground pegs were initially used to anchor the screen mats and improve mat contact with the earth. Subsequently, ground pegs were tested in various physical configurations from 2 to 50 pegs maximum, with various spacings, connected together by a 1/8-inch-diameter horizontal stranded steel surface cable. A 3-pound hand-held hammer was used to drive the pegs into the ground. Figure 4 shows the final design of the surface wire with ground pegs used during the comparative field tests. It consisted of 100 feet of 1/8-inch stranded steel cable secured to the ground every 4 feet by 6-inch pegs (26 total).

A stranded steel cable one-eighth of an inch in diameter and 100 feet long was tested as a horizontal buried wire. The depths tested varied from about half an inch to 6 inches. A special plow and wire spool were designed and made in the HEL shop for trenching and laying this wire (see Figure 5). These were designed for easy attachment to the rear of any standard Army truck.

Figure 1. Standard Army ground rod.

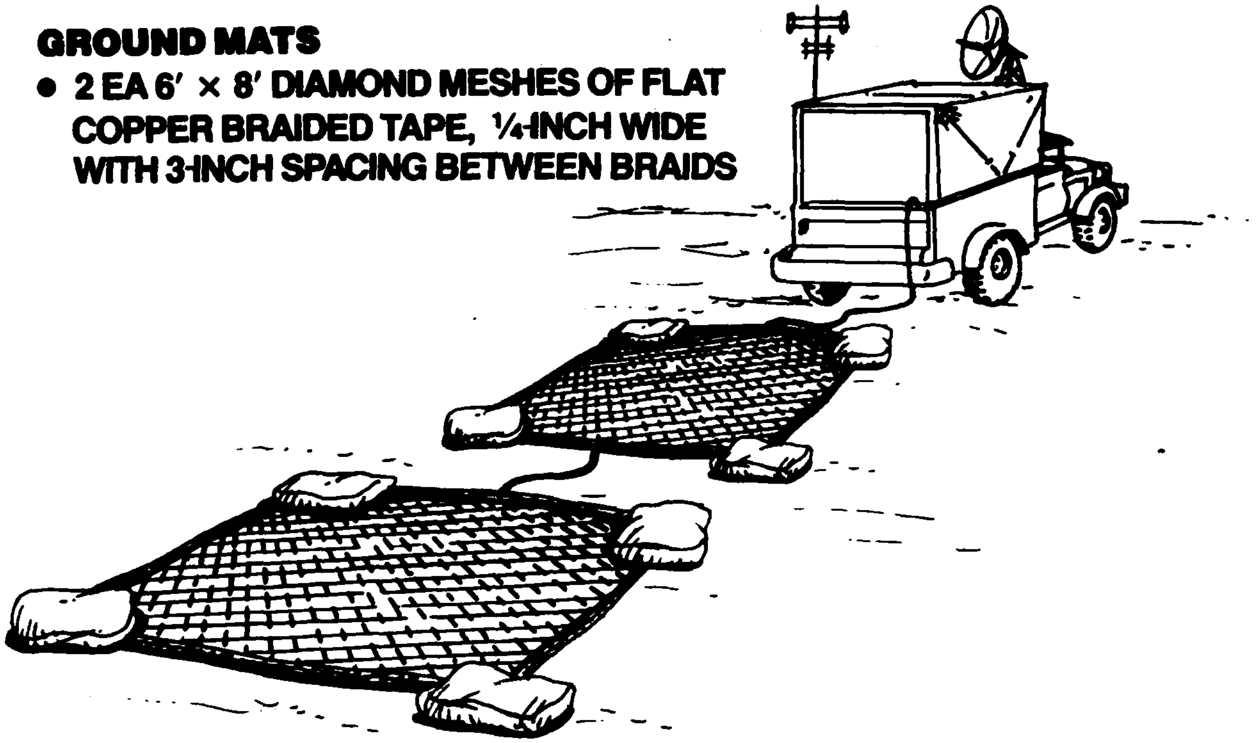

Figure 2. Ground mats.

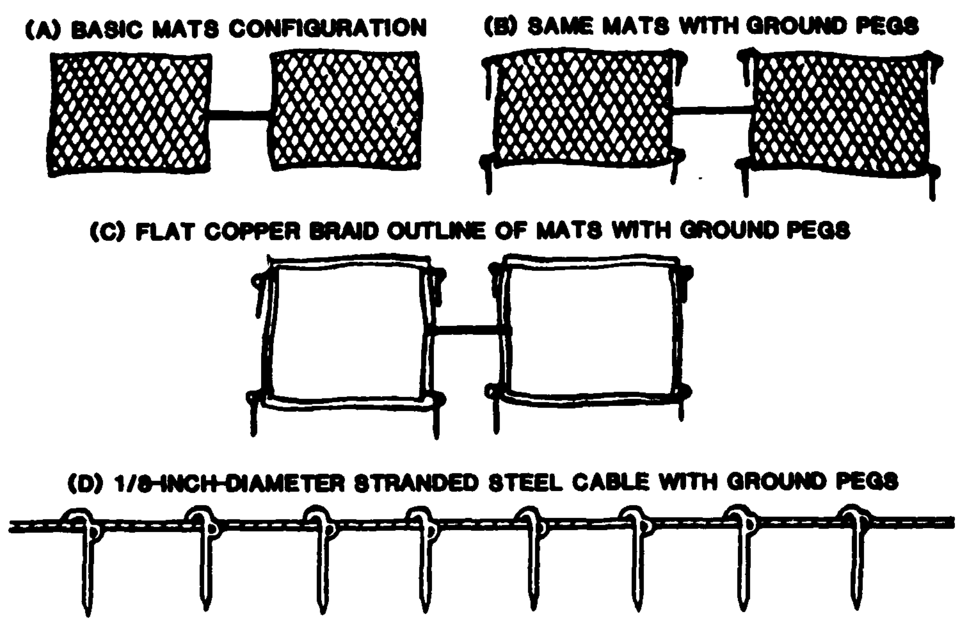

Figure 3. Surface wire with ground pegs development.

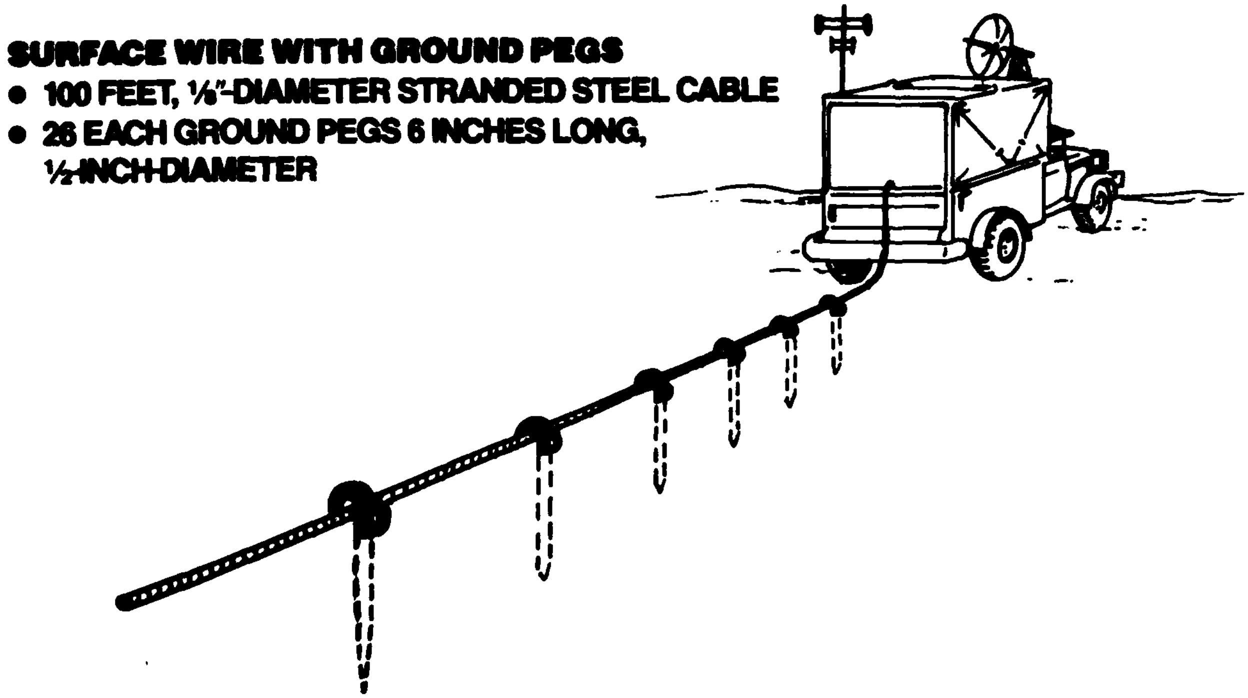

Figure 4. Surface wire with ground pegs.

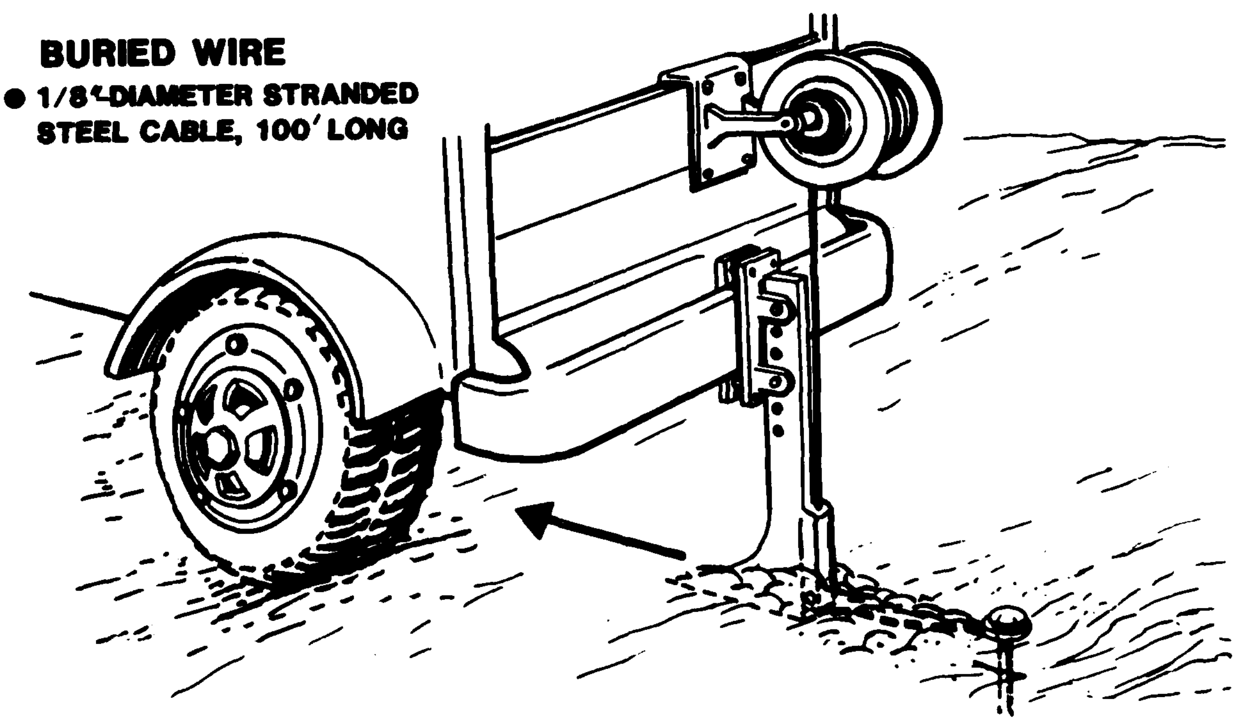

Figure 5. Buried surface wire configuration.

Phase II - Field Testing

Upon completion of the exploratory work, the three basic alternative earth-electrode designs (i.e., the mat, buried wire, and surface wire grounding systems) were stabilized and tested against the standard 6-foot ground rod at the following locations:

Aberdeen Proving Ground, Maryland
Fort Drum, New York
Fort Bliss, Texas
Yakima Firing Center, Washington
Fort Lewis, Washington
Fort Story, Virginia
Fort Huachuca, Arizona

Comparative baseline measurements of resistance, installation time, and removal time were made. Soil resistivity profiles were also made at each of the test sites.

Phase III - Enhancement Techniques

During Phase II, several grounding enhancement techniques were tested and evaluated in an effort to bring the typical grounding system resistance down to the 10-ohm standard specified in MIL-STD-188-124 (DoD, 1978). The following procedures were conducted at Fort Lewis, Washington:

<u>Chemical Enhancement Techniques</u>. For vertical systems, four 6-foot long ground rods were driven into the soil in a square array with 12 feet on each side (see Figure 6). Rod #1 was driven dry and remained dry throughout the test. Rod #2 was driven dry and the soil around it was wetted down with water only. Rod #3 was driven into a basin trench and the trench was then filled with rock salt, dirt, and water. Rod #4 was driven in dry soil and a doughnut trench shoveled out around it. The trench was filled with rock salt, water, and dirt. This last technique is illustrated in MIL-HDBK-419 (DoD, 1982). The resistance of each ground rod was measured at various time intervals after the application of water and salt.

Enhancement techniques for the two horizontal ground wire systems (surface wire with ground pegs and buried wire) consisted of the application of water and salt. For the surface wire design, a handful of salt was dropped over each of the ground pegs and water was poured over the entire length of the surface wire. For the buried wire design, salt water was poured over the furrow for the entire length of the wire.

<u>Multiple Earth-Electrode Enhancement Techniques</u>. At many sites, there are more than one CE facility present; therefore, we considered it advantageous to investigate the ramifications of connecting multiple earth-electrode systems. Since this would especially hold true for the surface wire concept (its length and above-ground environment

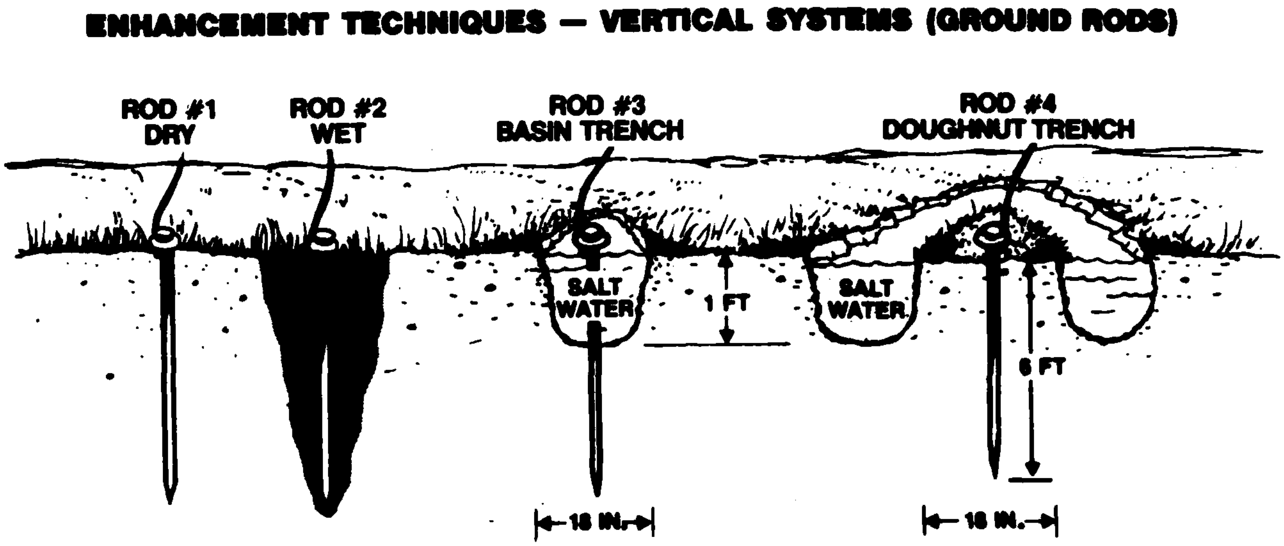

Figure 6. Enhancement techniques - (Ground rods).

facilitates interconnection), testing was concentrated on that design. Two surface wire systems were placed parallel to each other, about 40 feet apart and tested. Resistance measurements were taken on each surface wire independently and then when the surface wire was interconnected with an insulated wire.

Measurements

During all three phases, two primary measurements were taken using the null-balance earth tester (Megger®): soil resistivity and earth-electrode system resistance. In addition to resistance and resistivity measurements, other data were collected during Phase II that pertained to human factors involved in the use of various earth-electrode configurations. At each site and for each configuration tested, the approximate times for installation and removal of the earth-electrode systems were recorded. In addition, the procedures were observed and the number of personnel involved for each configuration was noted. The weight of each complete configuration (including tools required) was measured and the approximate storage parameters were calculated.

Earth-Electrode Resistance Measurement. The "fall-of-potential" method uses a Megger® to measure the resistance to earth of various types of earth-electrode systems. An alternating test current, generated by turning a hand crank on the test set, is injected into the earth between the earth electrode being tested (C_1) and a current probe (C_2) located some distance away, as shown in Figure 7. A third probe (P_2) is located between C_1 and C_2. The voltage drop between C_1 and P_2 is detected and balanced against an equal voltage in the test set (see Figure 8). The null condition is obtained by inserting resistance through the tester equal to the earth resistance between C_1 and P_2.

The resistance in the test set can be varied from 0.01 ohms to 9,990 ohms. The test set cranking speed can be varied to avoid interference from any stray currents present during measurements. The cranking speed governs the frequency of the alternating current. At a constant cranking speed of two-and-one-half revolutions per second, the frequency generated will be approximately 100 Hz. The potential generated is approximately 100 volts. When the proper amount of resistance is inserted in the potential circuit, no current will flow and the resistance of the potential probe will not affect the reading.

As the potential probe, P_2, moves away from the earth electrode, C_1, towards C_2, the balancing resistance is measured at several intermediate positions along the straight line between the two. These values, plotted as resistance versus distance from the earth electrode, are shown in Figure 9. As the potential probe (P_2) moves away from the earth electrode (C_1), the resistance values increase to a certain point, begin to level off, then increase again as the P_2 probe approaches the C_2 probe. The correct resistance to earth of the earth electrode (C_1) is the value at the leveled off portion of the curve, before

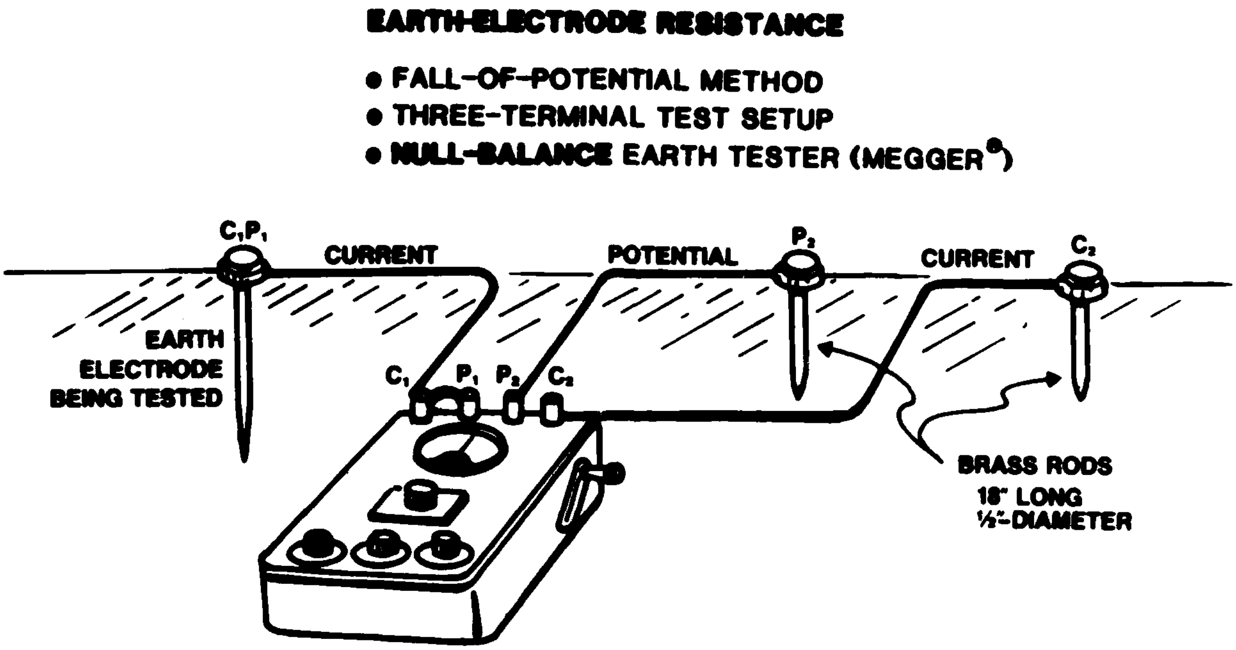

Figure 7. Resistance measurement test setup.

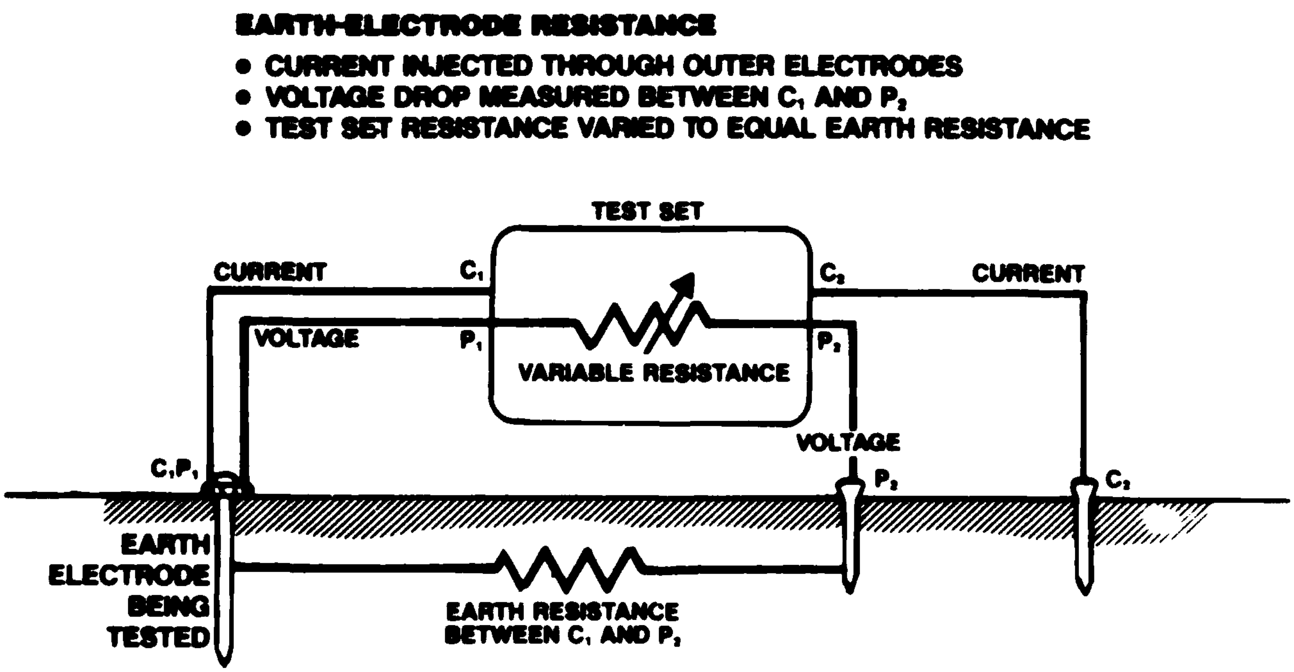

Figure 8. Resistance measurement electric schematic.

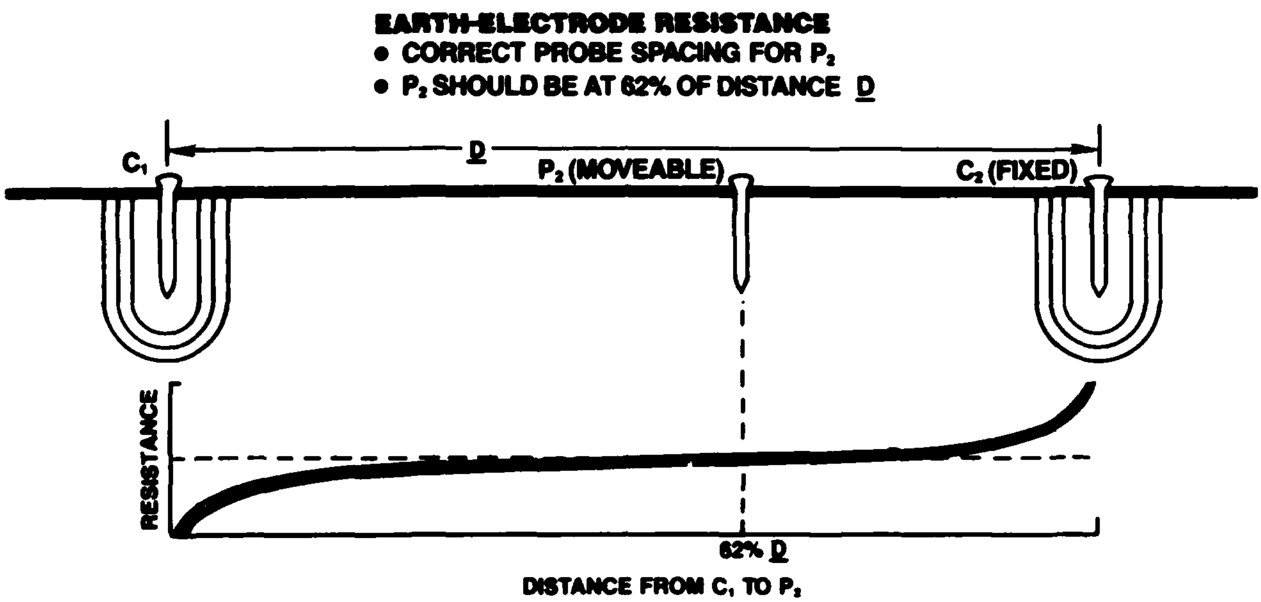

Figure 9. Locating the P_2 probe.

the P_2 probe approaches the area of influence of the C_2 probe. The correct resistance is usually obtained if the P_2 probe is placed away from C_1 at about 62 percent of the total distance between C_1 and C_2.

To explain this phenomenon, as the potential probe (P_2) is moved away from the earth electrode (C_1), the earth shells around C_1 continue to have greater and greater surfaces. The density of the constant test current is so dissipated over the larger earth shells that very little additional resistance is encountered as P_2 moves out of the area of influence of C_1. As P_2 is moved closer to C_2, the higher current-density earth shells around C_2 result in higher incremental resistance values, thus increasing the total resistance.

However, if C_2 is not located far enough away from C_1, their earth shells will overlap and the measured resistance, as P_2 is moved away from the earth electrode (C_1), will not level off. As a practical rule of thumb, when testing a single ground rod, good resistance measurements will be obtained if C_2 is placed at least 50 feet away from the rod (Biddle Instruments, 1982, p. 23). If the earth-electrode system consists of several rods or plates in parallel, or in other complex configurations, the rule of thumb calls for a spacing between C_1 and C_2 of five times the longest diagonal of the area of the electrode system under test (see Figure 10). The C_1 terminal should be connected to the center of the electrode system under test. The direction of the C_2 electrode from C_1 has only minor effects on the accuracy of the earth resistance measurement, providing the area selected is free of other metal objects and the measurement area is reasonably homogeneous.

Soil Resistivity Measurement. Soil resistivity measurements are valuable in identifying sites that will provide good earth-electrode grounding-resistance values. Such measurements can also be taken to obtain a soil resistivity profile. This profile is useful in finding the best physical configuration and depth for an effective, low-resistance earth-electrode system.

Resistivity values were calculated from resistance measurements made with the null-balance earth tester. The four-terminal method (Wenner, 1915) was used. Four electrodes are inserted into the soil in a straight line with equal spacings as shown in Figure 11. A known current is injected into the soil through the outermost electrodes (C_1 and C_2), and the voltage drop between the two inner electrodes (P_1 and P_2) is measured. As shown in Figure 12, resistance is inserted into the circuit through the tester until a null condition is achieved, i.e., until the inserted test resistance is equal to the earth resistance between the inner terminals.

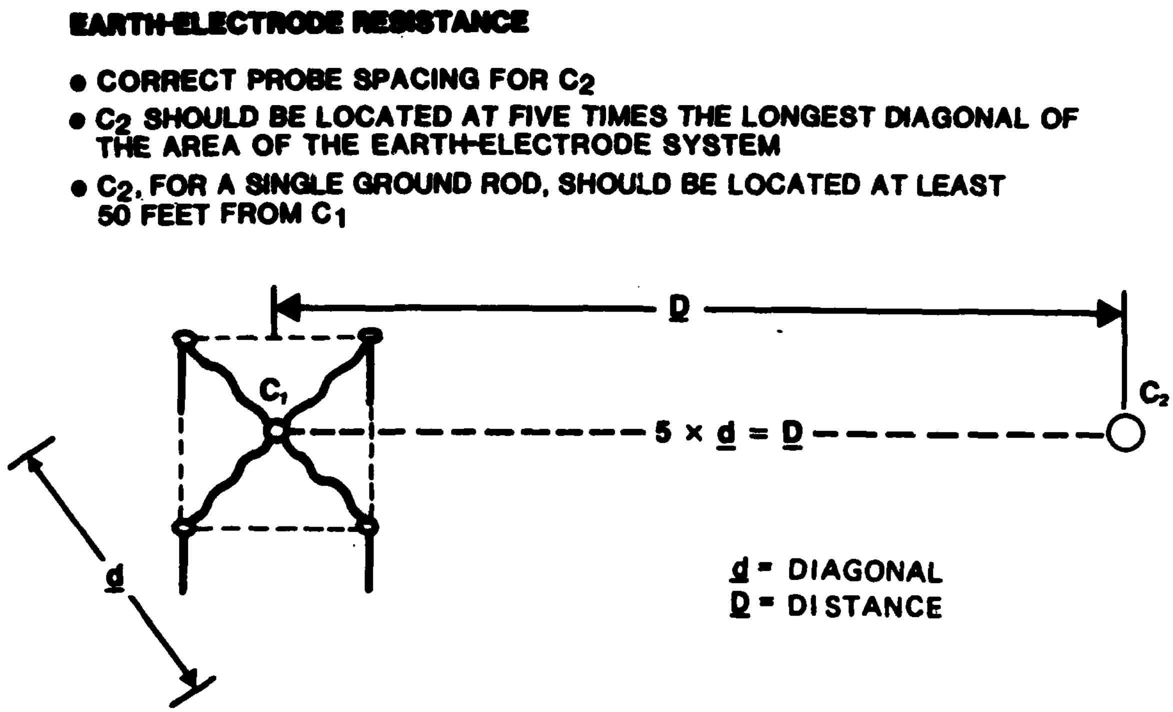

Figure 10. Locating the C_2 probe.

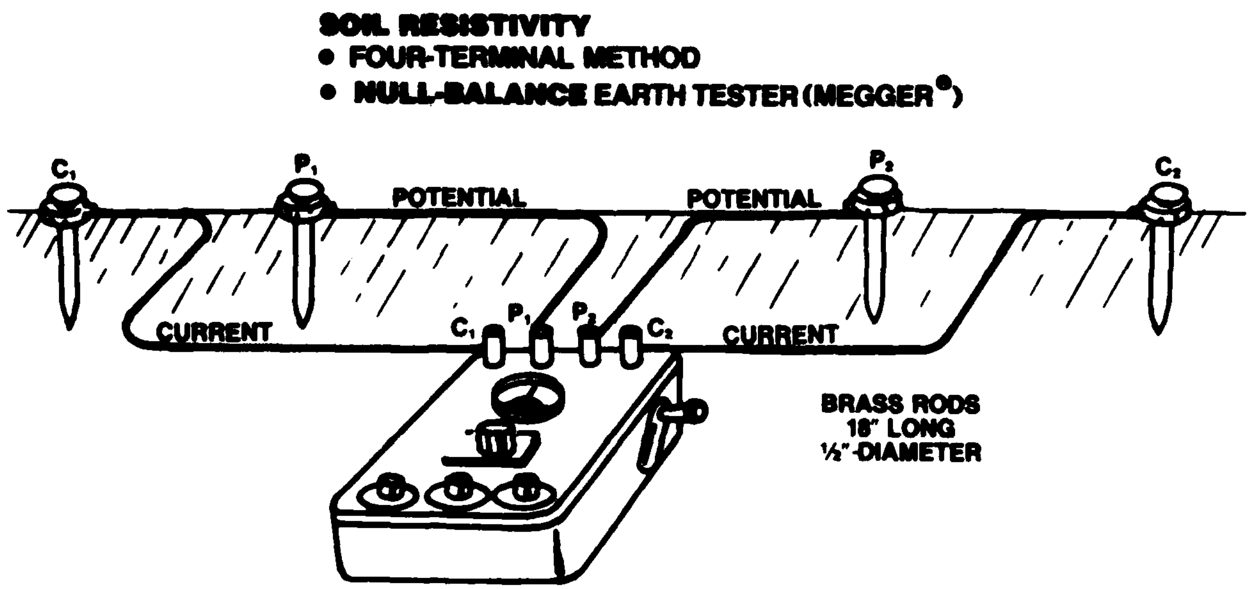

Figure 11. Resistivity measurement test setup.

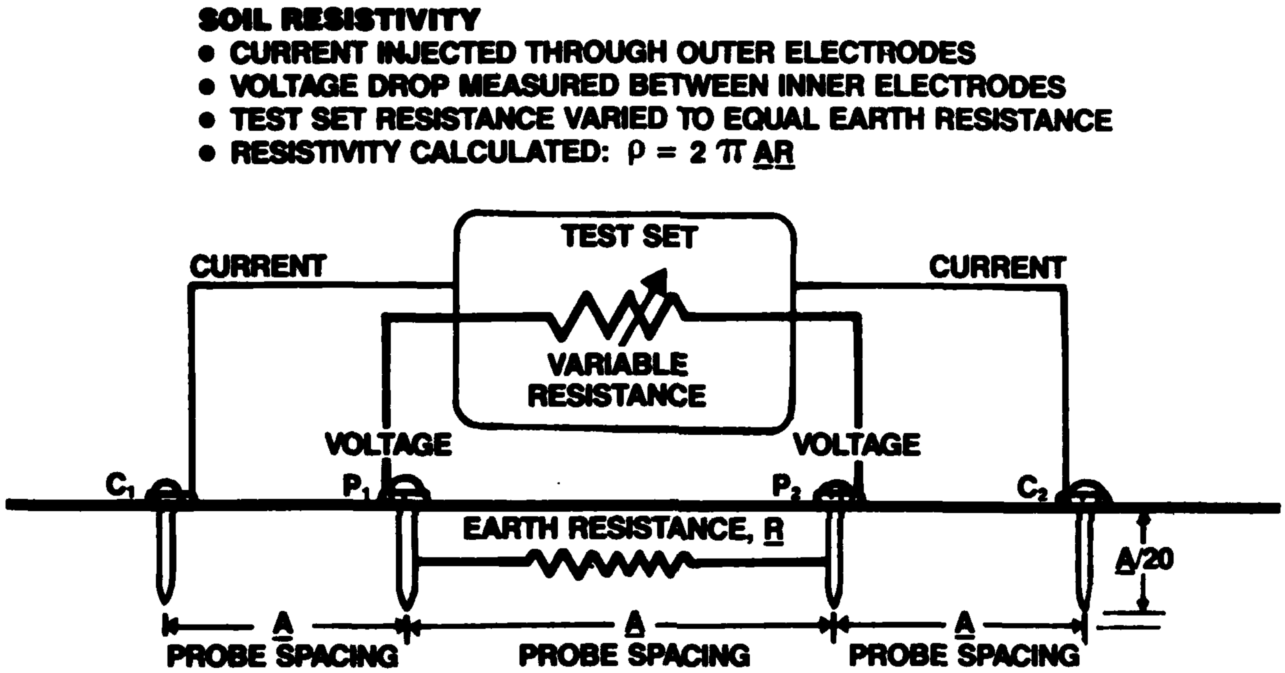

Figure 12. Resistivity measurement electric schematic.

Wenner showed that, if the electrode depth (d) is kept very small compared to the distance between the electrodes (A), the following formula applies: $\rho = 2 \pi A R$ where ρ is the average soil resistivity to a depth equivalent to A in ohm-centimeters. A is the distance between electrodes in centimeters and R is the null-balance earth tester resistance reading in ohms. The depth d, to which the electrodes are driven, should not be greater than 1/20 of A.

To obtain an indication of the soil resistivity at various depths below the surface, resistivity profile measurements were taken (see Figure 13). These surface measurements reveal below surface resistivity, because electrical current flows radially outward from the probes and downward, as well as along the surface. Successive resistivity measurements were made using this procedure. Electrode spacings (A) were depths from 2 feet to a maximum of 12 feet at 2-foot increments. These soil resistivity profiles provided a basis for understanding the differences in grounding effectiveness among the various configurations of earth-electrode systems. For example, at many of the sites the soil resistivity was found to increase with depth. At these sites, surface wire ground systems were as good or better than ground rods driven deeply into the soil. Thus, these profile measurements could also identify the best type of earth electrode to use at a particular site.

RESULTS AND DISCUSSION

In designing and installing an effective grounding system, it is important to know how earth electrodes dissipate electrical current into the soil. A brief discussion on this topic follows; a more complete discussion of the technical factors involved in grounding is provided in Appendix A. The primary results of each of the three phases of the study are also presented and discussed in this section (see Appendix B for additional data).

Technical Background

Effective grounding of tactical CE equipment is necessary for personal safety, for equipment and facility protection, and for reduction of electrical noise. Personal safety can be ensured by providing a low impedance path for currents due to electrical faults, to be shunted away from people to the ground. Equipment and facility protection are obtained by using circuit breakers and fuses. Electrical noise on communications circuits can be reduced by providing a low impedance ground path between signal ground point connections throughout the communications systems, by bonding between equipments, and by shielding noise sources. All of these types of grounding systems require a connection to an earth

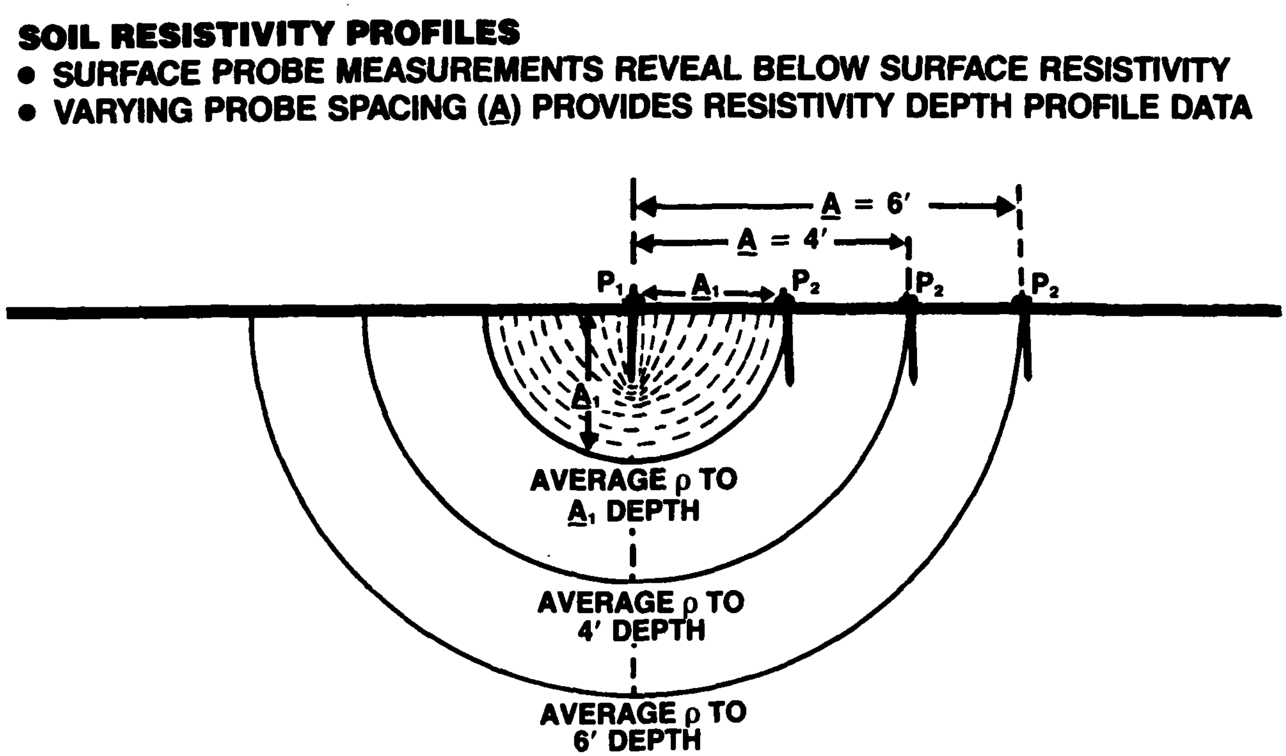

Figure 13. Resistivity profile measurement.

electrode to conduct electrical current to the ground potential (see Figure 14). The earth electrode makes direct contact with the earth and is the key element terminating all grounding systems.

The basic measure of effectiveness of an earth electrode is the resistance, in ohms, to the flow of electrical current into the surrounding earth. Grounding resistance requirements for CE facilities are outlined in several Army documents. One in particular, MIL-STD-188-124 (DoD, 1978), clearly describes the use of driven ground rods as a satisfactory earth-electrode subsystem. Also it states that when a ground rod does not provide a 10-ohm resistance to earth, alternative methods should be considered.

Figure 15 depicts how electrical current flows into the earth from a ground rod. It flows radially outward from the surface of the rod in all directions. It can be conceptualized as flowing through equipotential hemispherical shells concentric to the ground rod and perpendicular to the radial flow of current. As the constant amount of current flows from the ground rod, its density will decrease with distance away from the ground rod. This is because the areas of the successive shells become larger and larger with distance from the ground rod. The earth shell nearest the electrode naturally has the smallest surface area and so offers the largest resistance. The next earth shell is somewhat larger in area and offers less resistance. As the distance away from the electrode increases, the inclusion of additional earth shells does not add significantly to the total resistance of the earth to the flow of current. This area of influence of an earth electrode extends in all directions away from the rod, theoretically to infinity, with less and less influence as the distance increases.

The two basic factors affecting grounding are the soil characteristics and the physical design of the earth-electrode system. Every ground site has its own specific resistance to the flow of electrical current. This characteristic of the soil is called its resistivity. Soil resistivity, ρ, is usually expressed in terms of ohm-centimeters. It can vary widely among grounding sites, even when they are in close proximity to one another. This characteristic is affected by the type of soil, by its moisture and dissolved salt content, by temperature, and by seasonal changes.

For any given grounding site, the physical design of the earth-electrode system can have a major impact on its resistance to the flow of current into the earth. First, the more earth an electrode can connect with, the lower the resistance will be. Thus, increasing the length and diameter of an earth electrode will generally improve the effectiveness of the grounding. The use of earth electrodes also can provide a lower resistance grounding system. When multiple vertical earth electrodes are used, their spacing will be an important factor. If electrodes are too closely spaced, the total effectiveness of each one will not be realized. Because of overlap of their areas of influence, each electrode will have less earth available for absorbing the current flowing through it. As a general rule of thumb, the separation between vertical ground rods in a group of rods should be at least equal to or greater than twice the length of an individual rod.

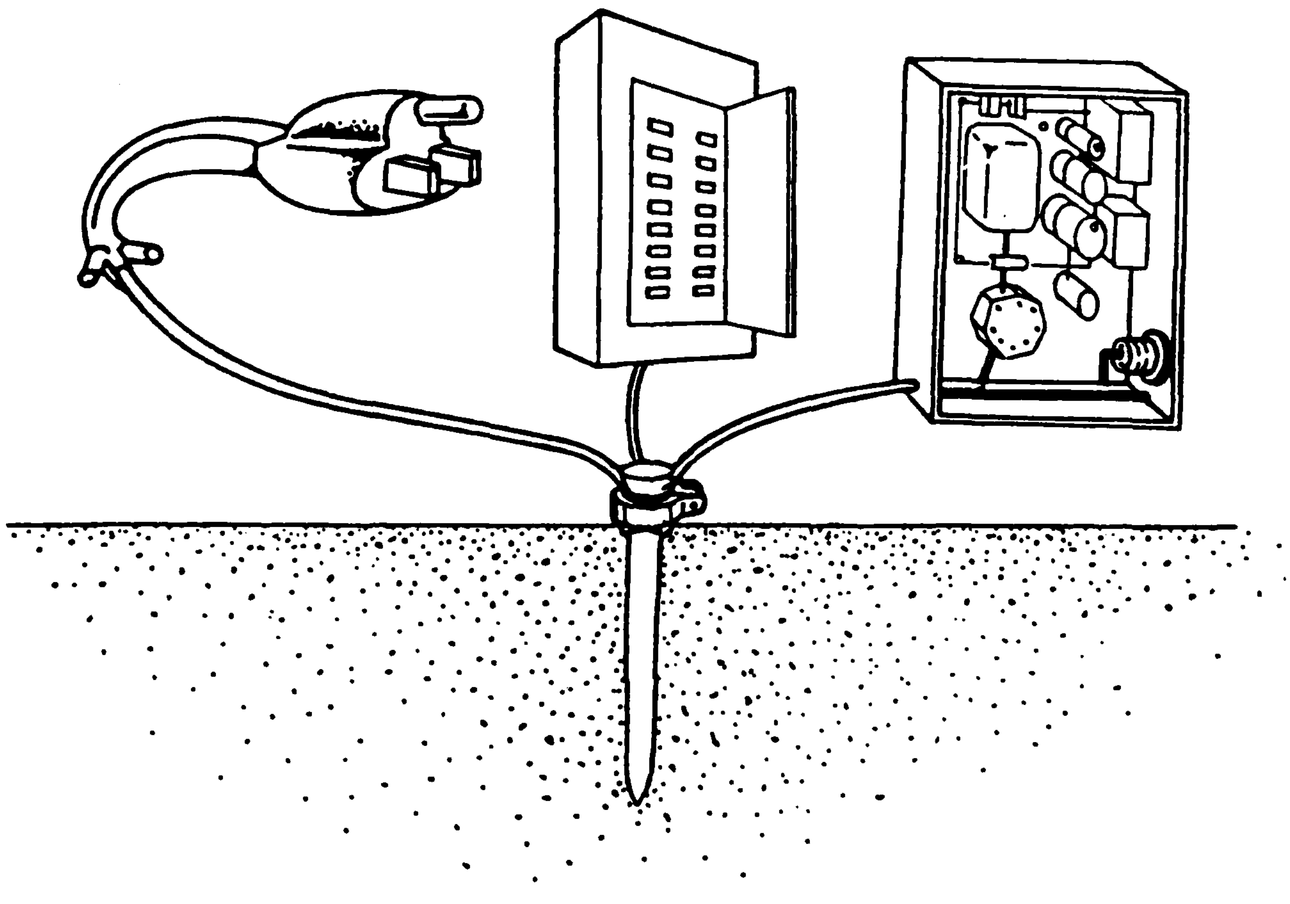

Figure 14. Earth-electrode system.

NATURE OF EARTH-ELECTRODE RESISTANCE

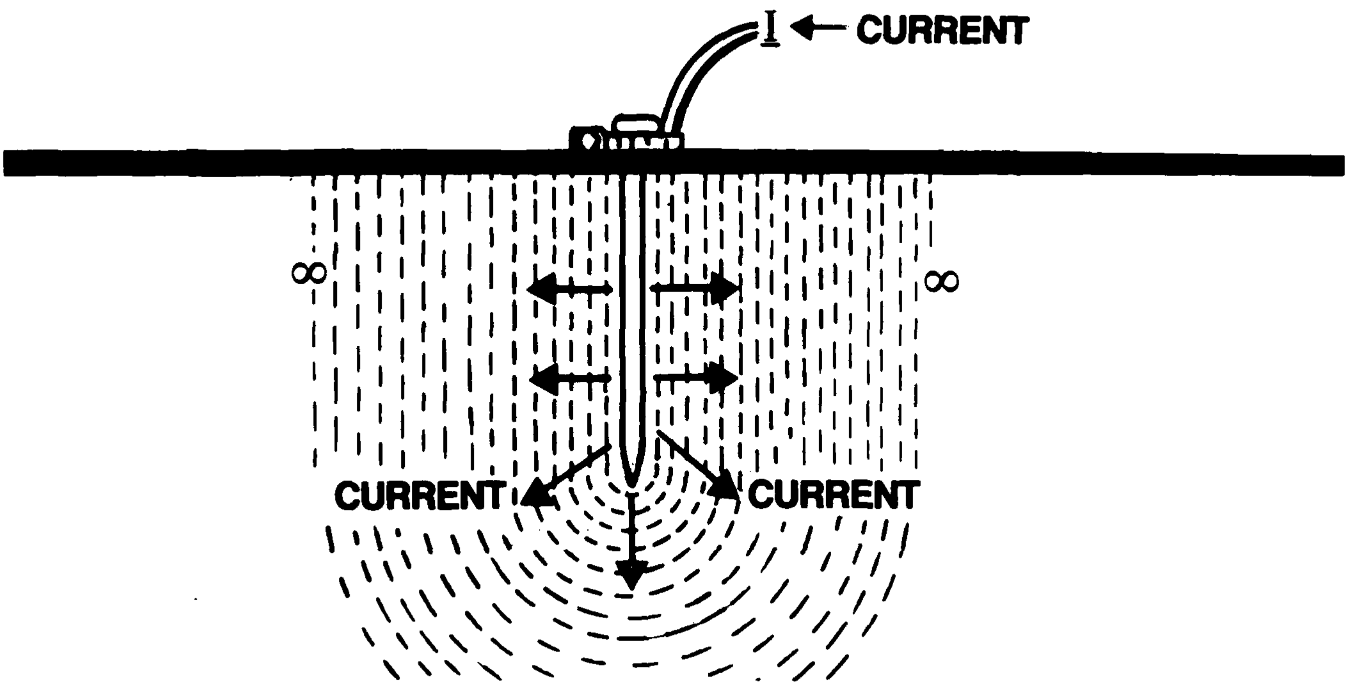

Figure 15. Current flow from ground rod.

Phase I - Exploratory Development

Tests were made at several sites on Aberdeen Proving Ground (APG), Maryland located near the Chesapeake Bay. Significant test results in front of Building 459, on 16 February 1984, are summarized in Table 1.

Table 1

Ground Rod, Mats, and Ground Pegs Data, Building 459, APG, Maryland (16 Feb 84)

Earth electrode	Resistance (ohms)
1 each 6' ground rod	128
2 each 6' x 8' mats, 50' separation between mats	518
Above mats with 4+4, 6[a] ground pegs	60
Above mats with ground pegs and cement blocks	50

[a]This notation means 4 ground pegs were used on each mat and they were driven 6 inches deep.

Another series of comparative test measurements were taken on 29 February 1984 at another location on APG--Phillips Army Airfield, on a plowed surface. Significant test results are summarized in Table 2.

Table 2

Ground Rods, Mats and Ground Pegs Data, Phillips Army Airfield, APG, Maryland (29 Feb 84)

Earth electrode	Resistance (ohms)
2 each 6' x 8' mats, 50' separation, 4+4, 6 (ground pegs insulated from mats)	651
Same as above, but ground pegs in contact with mat	184
Same as above, plus 7 sandbags on each mat	100
Same as above, plus 1 ground rod connected to mat	69
Same as above, plus 2 ground rods connected to mat	59
Same as above, plus 3 ground rods connected to mat	55

Tables 1 and 2 show that for these locations, the use of 6-inch ground pegs provided the most significant reduction in ground resistance over that obtained from a mat alone. In the first test series (Building 459) the 8 ground pegs with the mats (4 on each mat) provided a more effective grounding than the single 6-foot ground rod alone. In both series adding weight on the mats improved the performance of the mats. The addition of ground rods to the ground-pegged, weighted mats also improved the grounding; but to a lesser degree than the addition of either the ground pegs alone or the weights.

These results indicate that the ground pegs around the periphery of the mats were contributing the major component of the grounding effect. Therefore, a new earth-electrode system was designed using 3/4-inch flat copper braided tape placed on the surface of the ground to form the outline of the 6-foot by 8-foot mats, with a 50-foot separation, connected by a length of copper braid (refer back to Figure 3). Various quantities of the steel ground pegs were added to the braided tape outline of the mats and driven to various depths in the ground. Table 3 summarizes the significant results of tests done on the ground-pegged mats and the ground-pegged outline. Both configurations were tested at the same time in the same location with the ground-pegged mats tested twice and the ground-pegged outline tested once.

Table 3

Mats Versus Pegged Outline Resistance Data

Earth electrode	Resistance (ohms)	Date
6' x 8' pegged mats, 8+8, 10[a]	32	17 April 1984
6' x 8' pegged mats, 8+8, 10[a]	48	18 April 1984
Ground-pegged outline, 8+8, 10[a]	30	18 April 1984

[a]This notation means 8 ground pegs were used on each mat and they were driven 10 inches deep.

These results confirmed that the centers of the mats do not contribute significantly to earth grounding unless they are effectively weighted. In fact, the resistance was lower for the pegged outline than it was for the pegged mats. Increasing the quantity of ground pegs as well as their depth further improved the grounding effectiveness of the ground-pegged outline.

Based on the results in Table 3, a test was made to determine the grounding performance of the same braided wire tape and ground pegs if they were laid out in a straight line instead of in the outline of the mats (see Table 4).

Table 4

Braided Surface Wire With Ground Pegs Resistance Data (20 April 84)

Earth electrode	Resistance (ohms)
Pegged outline, 12+12, 10[a] (76 ft long) (20 ft separation)	25
Straight line, 12+12, 10[a] (76 ft long)	22

[a]This notation means 12 ground pegs were used on each mat and they were driven 10 inches deep.

Tests were then made on the effect of adding more 6-inch ground pegs to the straight braided wire and the effect of the spacing of the ground pegs (see Figure 16). Two series of tests were conducted. One series of tests (see series A in Figure 16) started with two pegs at the center of the wire (1 foot apart) and added two pegs at a time (at 2-1/2-foot intervals) from the center outwards for a total of 24 pegs. The second series of tests (see series B in Figure 16) started with all 24 pegs in place, then removed two at a time from the center outwards until only the outermost two pegs remained. The resistance of each configuration of ground pegs was measured. The surface wire used for these tests was approximately 130 feet long. For the first series of tests, only about 1 foot of surface wire was in contact with the soil at the start. The remaining wire was coiled up on insulating material. As the additional ground pegs were added, the wire was uncoiled to a maximum length of about 56 feet of surface wire in contact with the soil. Tables 5 and 6 show the results of these tests conducted at Building 459 on APG.

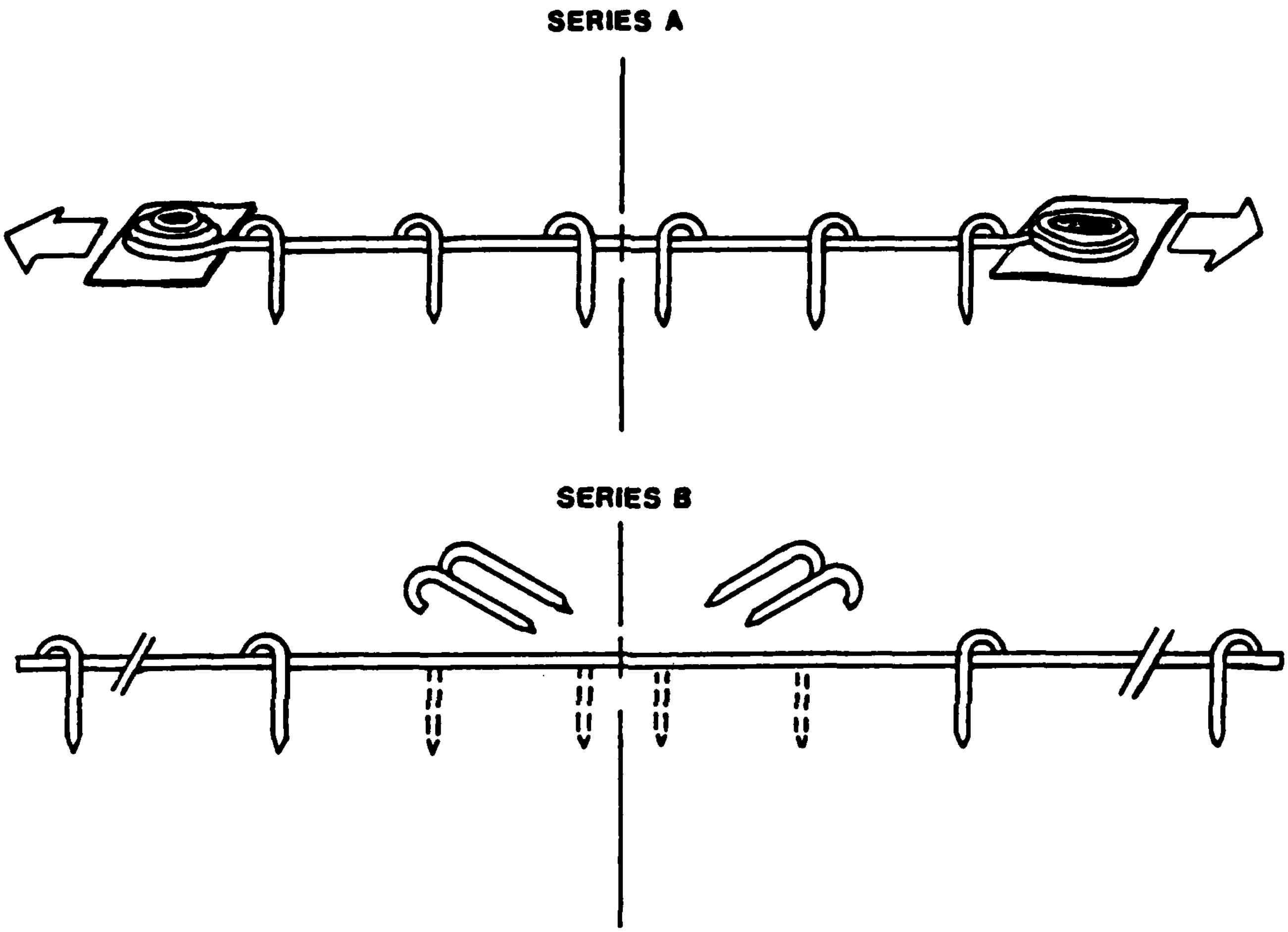

Figure 16. Effect of ground peg spacing.

Table 5

Effects of Multiple Pegs and Spacing, Series A and B

	Test Series A		Test Series B	
Total pegs	Inner/outer separation (feet)	Resistance (ohms)	Inner/outer separation (feet)	Resistance (ohms)
1+1	1/1	191	56/56	153
2+2	1/6	121	51/56	89
3+3	1/11	87	46/56	67
4+4	1/16	68	41/56	56
5+5	1/21	56	36/56	50
6+6	1/26	49	31/56	45
7+7	1/31	45	26/56	51
8+8	1/36	41	21/56	37
9+9	1/41	38	16/56	33
10+10	1/46	35	11/56	31
11+11	1/51	31	6/56	30
12+12	1/56	29	1/56	29

The innermost pegs were then separated by 50 feet and the two series of observations were repeated (Series C and D) as summarized in Table 6.

Table 6

Effects of Multiple Pegs and Spacing, Series C and D

	Test Series C		Test Series D	
Total pegs	Inner/outer separation (feet)	Resistance (ohms)	Inner/outer separation (feet)	Resistance (ohms)
1+1	50/50	148	105/105	133
2+2	50/55	89	100/105	81
3+3	50/60	68	95/105	59
4+4	50/65	54	90/105	48
5+5	50/70	45	85/105	41
6+6	50/75	39	80/105	37
7+7	50/80	34	75/105	33
8+8	50/85	30	70/105	30
9+9	50/90	28	65/105	28
10+10	50/95	26	60/105	26
11+11	50/100	23	55/105	24
12+12	50/105	21	50/105	23

Results from Series A through D show that the more pegs, the lower the ground resistance obtained. They also show that the greater the separation of the same number of pegs, the lower the ground resistance. This would also be expected because the greater spacing reduces the overlapping areas of influence among pegs, thus allowing greater reduction of ground resistance (or greater grounding effectiveness) to be realized from each ground peg.

Designs with straight surface wire, buried wire, and surface wire with pegs were then tested. A 125-foot steel wire cable, with a 3/32-inch-diameter was laid on the ground and the ground resistance measured. Weights were then added to improve contact with the earth. Finally, the wire was buried 1/2 to 1 inch for still better earth contact. The results are summarized in Table 7.

Table 7

Surface Wire, Buried Wire, and Ground Pegs Data

Earth electrode	Resistance (ohms)
Surface wire (125 feet long, 3/32-inch-diameter)	1,480
Surface wire with 6+6 sandbags[a]	267
Surface wire with 6+6 sandbags and 5+5 cement blocks[b]	186
Buried wire (1/2 to 1 inch deep)	10

[a]This notation means 6 sandbags were used on each mat.
[b]This notation means 5 cement blocks were used on each mat.

The effect of length on resistance of buried wire was then tested by removing approximately 2.5 feet from each end between each measurement. The results indicate that the resistance was inversely proportional to the wire length. The data are shown in Table 8.

Table 8

Effect of Length of Buried Wire

Length (feet)	Resistance (ohms)
122	12
117	13
112	14
107	15
102	16
97	17
92	19
87	19
82	20
77	21
72	22
67	24
62	26
57	28
52	30
47	33
42	37
37	40
32	47
30	49

The effect of changing the depth of the buried wire was tested. The results show reduced resistance with increased depth. The data are summarized in Table 9.

Table 9

Effect of Depth of Buried Wire

Depth (inches)	Resistance (ohms)
1/2	57
1	36
1-1/2	32
2	31
2-1/2	31

The effect of wire diameter on ground resistance was tested. The uninsulated stranded wire cables were 30 feet long and buried 2 to 2-1/2 inches deep. Results show reduced resistance with increased wire size as summarized in Table 10.

Table 10

Effect of Diameter of Buried Wire

Wire size (inches)	Resistance (ohms)
3/32	94
1/8	83
3/16	53
1/4	48

Based on the effectiveness of buried wire, as indicated by the data in Table 10, a plow was designed, built in the HEL shop, and tested to determine feasibility for operational use. The plow was easily and quickly attached to the rear bumper of an Army truck and it operated effectively in implanting the surface wire. The results of these exploratory tests using 1/8-inch buried wire at the old airport on APG are summarized in Table 11.

Table 11

Buried Wire With Plow Data, Old Airport, APG, Maryland

Earth-electrode length (feet)	Resistance (ohms)
30	169
60	152
90	114
150	90
180	80

Soil profile resistivity measurements at three locations on APG showed different soil characteristics. At the Building 799 site, the average resistivity near the surface (ρ = 50,000 to 55,000 ohm-cm at 4-foot depth) was lower than at greater depths (ρ = 70,000 to 84,000 ohm-cm at 8-foot depth). At the Old Airport site, soil resistivity decreased with increased depth (ρ = 16,000 ohm-cm at 2-foot depth; ρ = 7,800 ohm-cm at 10-foot depth).

Phase II - Field Testing

Resistance and Resistivity Data

Upon completion of the exploratory work, three basic alternative earth-electrode designs (the mat, buried wire, and surface wire grounding systems) were established for comparative measurement at various field sites against the baseline 6-foot ground rod. Selected baseline data for each of these sites are summarized in Tables 12 through 21. Additional data are provided in Appendix B.

Aberdeen Proving Ground, Maryland. Comparative measurements were made at three test sites: the old airport, Building 799, and Phillips Army Airfield. As previously mentioned, APG is located near the Chesapeake Bay, a large estuarial body of water.

Old Airport Results (Table 12): The soil can be characterized as loam fill, with the temperature at approximately 60 °F. The surface was moist from a ground fog.

Table 12

Baseline Data, Old Airport, APG, Maryland

Resistance measurements	
Earth electrode	Resistance (ohms)
6' ground rod	46
Mats with 12 sandbags	107
100' surface wire with 26 ground pegs 6" long	37
200' surface wire with 26 ground pegs 6" long	21
100' buried wire	38
200' buried wire	20

Resistivity profile

A (feet)	ρ (ohm-cm)
2	15,972
4	15,243
6	9,583
8	7,875
10	7,775

Building 799 Results (Table 13): This site was snow-covered (1 inch deep) with the temperature at about 34 °F during the test.

Table 13

Baseline Data, Building 799, APG, Maryland

Resistance measurements	
Earth electrode	Resistance (ohms)
6' ground rod	248
Mats with 12 sandbags	135
100' surface wire with 26 ground pegs 6" long	61
100' buried wire	36

Resistivity profile	
A (feet)	ρ (ohm-cm)
2	13,023
4	25,526
6	31,714
8	42,439
10	54,198

Phillips Army Airfield Results (Table 14): This site was frozen to a depth of approximately 4 inches. The temperature was about 17 °F.

Table 14

Baseline Data, Phillips Army Airfield, APG, Maryland

Resistance measurements	
Earth electrode	Resistance (ohms)
6' ground rod	100
Mats	243
100' surface wire with 26 ground pegs 6" long	70
100' buried wire	189

Resistivity profile	
A (feet)	ρ (ohm-cm)
2	24,513
4	23,593
6	28,497

APG Discussion: The results at APG show how various soil resistivity and local weather conditions can affect the grounding effectiveness of different earth-electrode configurations. At all three sites the surface wire or buried wire (horizontal earth electrodes) performed better than a single ground rod.

At the Old Airport site, the soil resistivity decreased with depth and the ground rod penetrating into lower resistivity soil performed relatively well. Its 46-ohm resistance was only slightly higher than the surface wire (37 ohms) and buried wire (38 ohms) values. The mat did not make good overall contact with the soil because of the grass. Hence, it had the highest resistance value (107 ohms).

The results at Building 799 show the adverse impact on vertical ground rod performance (248 ohms) where soil resistivity increased with depth. The rod penetrated into higher resistivity soil resulting in a high resistance value. Near the soft wet surface, on the other hand, the surface wire and buried wire both gave lower resistance values. Here again, the mat may have been in poor contact with the soil, due to the snow covering, which can act as an insulator.

At Phillips Army Airfield, the dominant factor appears to be the frozen top layer of soil (at 17 °F). It probably insulated the mats and the buried wire (shallow covering of frozen soil) causing these to give the highest resistance values. The soil resistivity remained relatively constant with depth. This gave the surface wire with ground pegs the advantage over the ground rod because of the relatively greater surface area of the 26 ground pegs in contact with the soil below the frozen surface level.

Fort Drum, New York. Measurements were made at two test sites on Fort Drum.

Area 12B Results (Table 15): This site was snow-covered with temperatures at or below freezing during the test period.

Table 15

Baseline Data, Area 12B, Fort Drum, New York

Resistance measurements

Earth electrode	Resistance (ohms)	
	26 February 1985	28 February 1985
6' ground rod vertical	44.5	44.1
Mats with pegs at corners	171[a]	455[a]
100' surface wire with 26 ground pegs 6" long	104[a]	157[a]
100' buried wire	39.9 (in thawed earth)	9,990+ (in snow)

Resistivity profile on 26 February 1985

A (feet)	ρ (ohm-cm)
2	37,613
4	20,607
6	11,953
8	7,805

[a]Snow hampered contact of surface wire and mats with earth.

Area 4C Results (Table 16): The ground was frozen hard and snow-covered, with a temperature of 26 °F.

Table 16

Baseline Data, Area 4C, Fort Drum, New York (28 Feb 85)

Resistance measurements	
Earth electrode	Resistance (ohms)
6' ground rod horizontal (in snow)	9,990+
Mats pegged (8 each) at corners	7,490
100' surface wire with 26 ground pegs 6" long	135
100' buried wire (frozen soil)	111

Resistivity profile	
A (feet)	ρ (ohm-cm)
2	344,338
4	735,406
6	1,608,700
8	1,516,775
10	1,637,427

Fort Drum Discussion: The results at Fort Drum indicate the wide variation in soil resistivity characteristics for two sites relatively close to each other. At Area 12B, the soil resistivity was relatively low and it decreased as depth increased. At Area 4C, on the other hand, the resistivity values were an order of magnitude higher, and they increased with increased depth. At Area 12B, vertical ground rods penetrating into lower resistivity soil were more effective than the shallow ground pegs with surface wire. On the other hand, at Area 4C, the laying of the ground rod horizontally in the snow proved not to be as profitable as was suggested in other literature on the subject. The lowest resistance (39.9 ohms) was obtained with the buried wire at Area 12B. One would not have expected such performance at this site because the soil resistivity was higher at the surface. This may have been due to the thawed condition of the soil. The moisture probably provided an enhanced path for the flow of electrical current into the soil along the entire surface area and length of the wire.

Fort Bliss, Texas. This site at the Biggs Army Airfield is characterized as normally sandy soil. Measurements were made after heavy rains and the soil was wet. Resistivity profiles were taken at four locations, all in the same general area (see Table 17).

Table 17

Baseline Data, Fort Bliss, Texas

Resistance measurements

Earth electrode	Resistance (ohms) 18 March 1985	Resistance (ohms) 19 March 1985
6' ground rod vertical	62.2	b
Mats (sand-covered) pegged	18.97	17.6 (57.9[a])
100' surface wire with 26 ground pegs 6" long	39.2	16.2
100' buried wire 8" deep	23.1	b

Resistivity profile (17 March 1985)

A (feet)	ρ (ohm-cm) Location 1	Location 2	Location 3	Location 4
2	17,992	b	13,368	11,146
4	11,102	10,648	10,265	7,967
6	9,682	7,929	8,158	6,780
8	8,591	7,048	8,580	6,896
10	8,824	6,511	9,193	7,086
12	9,257	6,435	10,571	7,354

[a]Mats (sand removed).
[b]Circumstances prohibited the collection of specific data.

Fort Bliss Discussion: The 6-foot vertical ground rod was clearly the least effective of all earth-electrode configurations tested. The data did not provide clear evidence, however, of the most effective grounding system. The sand-covered mats showed the lowest resistance on the 18 March test, while the surface wire with ground pegs showed the lowest resistance on 19 March after a heavy rain.

The soil resistivity data for Locations 3 and 4 revealed a decreasing resistivity with depth until the 6-foot level was reached, at that point there was a layer of increasing resistivity. At Location 2 resistivity continued to slowly drop below the 6-foot level. At Location 1 resistivity began to rise at the 10-foot depth.

Yakima Firing Center, Washington. This area is basically desert terrain, with ridges of hard ground and rock rising above dry, sandy valleys. Several test sites were attempted before one was found where vertical ground rods could be fully driven into the soil. Location 1 was about halfway up the side of a ridge known as Hog Ranch Butte. Location 2 was about 400 yards farther down the hill. At both of these locations, after about 30 minutes of effort by three men using a 10-pound sledge hammer, the ground rod could only be driven about 2 feet into the hard soil. Moving farther down the hill, a site (Location 3) was found where ground rods could be driven completely into the soil. Here again, however, it required about 30 minutes of strenuous effort to complete the task. This site was considered acceptable because the vegetation was thicker, indicating the possibility of a deeper layer of soil.

Soil resistivity measurements were taken at all three locations. Resistance measurements of the earth electrodes were confined to Location 3. These results are shown in Table 18.

Table 18

Baseline Data, Yakima Firing Center, Washington

Resistance measurements

Earth electrode	Resistance (ohms) Location 3
6' ground rod vertical (installed 5/15, removed 5/17)	99-117 over 2-day period
Mats with 6 sandbags and 8 pegs (5/15)	140
100' surface wire with 26 ground pegs (5/15)	35
200' surface wire with 43 ground pegs (5/15)	27
100' buried wire 4" to 6" deep (5/17)	129

Resistivity profiles

A (feet)	ρ (ohm-cm) Location 1	Location 2	Location 3
2	a	a	8,505
4	7,584	25,969	8,503
6	13,099	30,565	8,963
8	14,080	31,101	9,805
10	16,068	33,323	9,193
12	13,926	34,012	8,963

[a]Circumstances prohibited the collection of specific data.

Yakima Discussion: The soil resistivity measurements at all three locations generally showed an increased value with depth down to the 8- to 10-foot level, with some reduction in resistivity indicated at greater depths at two of the locations. Under such conditions, the poor performance of a single vertical ground rod (over 100 ohms) would be expected. At Location 3, where comparative baseline data could be obtained, the surface wire with ground pegs was clearly the most effective grounding system.

Fort Lewis, Washington. This area is covered with grass vegetation, but the soil appears grainy and somewhat sandy. Baseline data are in Table 19.

Table 19

Baseline Data, Fort Lewis, Washington

Resistance measurements

Earth electrode	Resistance (ohms)
6' ground rod vertical	7,190
Mats with 6 sandbags and 8 pegs	1,270
100' surface wire with 26 ground pegs (pegs loose, in poor ground contact)	744
100' buried wire	986 (489[a])

Resistivity profiles (all in same general area)

A (feet)	ρ (ohm-cm) Location 1	Location 2	Location 3	Location 4
2	1,566,564	880,900	877,123	838,770
4	1,754,245	1,532,000	528,572	1,217,940
6	2,298,138	1,838,400	907,764	1,482,210
8	1,530,560	2,006,920	1,377,350	1,224,068
10	1,158,645	1,909,255	1,338,665	1,338,585
12	850,311	1,838,400	1,238,696	1,376,502

[a]Vehicle driven over wire.

Fort Lewis Discussion: The tests were conducted on the Fort Lewis parade ground area. Several ground resistivity profiles were taken in the same general area, because the first readings were an order of magnitude higher than any that had been seen previously at other field sites. After the first readings, the Megger® was checked by the local electrical equipment calibration unit and found to be accurate. The instrument was tested as specified in Section II of Testing, paragraph 3 and 4, Range and Accuracy Check of Technical Manual TM-11-6625-2944-14 (Department of the Army, 1979).

The Fort Lewis parade ground area, where baseline tests were conducted, has an extremely high earth resistivity. It is essentially a large, thick insulator. The resistivity generally increases with greater depth down to about the 8-foot level, after which some resistivity decrease was noted. In this area, as at Yakima Firing Center where a similar resistivity inversion existed, a single vertical ground rod showed the poorest relative grounding performance. The pegged surface wire performed better than the buried wire before the buried wire was packed down by driving the vehicle over it. Several of the ground pegs did not make good contact because of the prevalence of small, rounded rocks in the soil. Ground pegs of greater length (perhaps 8 or 10 inches) would have made better contact with the soil and would have probably given lower resistance values.

Fort Story, Virginia. Fort Story provided a typical seacoast environment with a sandy beach and extended areas of sand dunes. Several sites were selected that would be expected to provide a variation in soil resistivity profiles. They were all parallel to the shoreline. Location 1 was in a draw between dunes about 200 yards from the water. The sand was quite dry in some spots, but damp in others. Location 2 was still in the draw, but nearer the water and uniformly damp. Location 3 was on the beach outside of the draw. At Location 4 the sand was slightly moist and firm. This last location was selected for testing the various earth electrodes (see Table 20).

Table 20

Baseline Data, Fort Story, Virginia

Resistance measurements

Earth electrode	Resistance (ohms) Location 4
6' ground rod vertical	12.5
6' ground rod horizontal (buried 8" deep)	37.9
Mats covered with sand (no ground pegs)	110
100' surface wire with 16 ground pegs	3.9
100' buried wire (hand-covered, 6" deep)	2.4

Resistivity profiles

A (feet)	ρ (ohm-cm) (8 July 85) Location 1	Location 2	Location 3	Location 4
2	a	10,494	a	1,195
4	229,800	10,034	253	1,716
6	114,900	11,950	931	2,574
8	4,596	13,115	858	2,712
10	112,990	13,425	957	3,466
12	22,981	13,420	1,103	4,091

[a]Circumstances prohibited collection of specific data.

Fort Story Discussion: The moist, salty, soil conditions on the Fort Story beach provided an excellent site for effective grounding. The buried wire and the surface wire with only 16 ground pegs both provided very low ground resistance values (under 5 ohms) and better grounding than the standard 6-foot vertical ground rod. The sand-covered mats had unusually high ground resistance relative to the other earth electrodes.

Soil resistivity was found to vary widely as a function of the moisture in the sand. At the top of the dunes, where the sand was dry, the resistance readings went beyond the upper limits (9,990 ohms) of the tester. The resistivity was also generally found to increase with depth at most locations. This may have been due to the residual surface salt from seawater washing over these areas.

Fort Huachuca, Arizona. Attempts to drive a ground rod into the soil were unsuccessful at two locations. At the Buckhor area #1985, ASA #703, a ground rod could only be driven 5 feet into the soil. This area is desert terrain, with rocky, coarse soil. The site at ASA #615 was very flat with high (about 18") grass growing in abundance. The surface was hard, down to about a 2" depth, below which it was relatively easy to drive the ground pegs into the soil. Table 21 contains baseline data for Fort Huachuca.

Table 21

Baseline Data, Fort Huachuca, Arizona

Resistance measurements

Earth electrode	Resistance (ohms)	
	ASA #703	ASA #615
5' ground rod vertical	39.2	61.4
Mats with 26 ground pegs and sand-covered	36.6	489[a]
100' surface wire with 26 ground pegs	17.0	153 (70[b])
100' buried wire	39.2 (9.9[d])	140 (28.7[c])

Resistivity profile

A (feet)	ρ (ohm-cm)	
	ASA #703	ASA #615
2	e	9,990
4	5,822	9,990
6	5,475	4,022
8	1,380	3,524
10	e	1,915

[a]Mats at this location included only 4 ground pegs each.
[b]Addition of water only (no salt).
[c]After driving over furrow.
[d]After walking over furrow.
[e]Circumstances prohibited collection of specific data.

Ft. Huachuca Discussion: The effectiveness of ground rods as compared with horizontal earth electrodes varied at the two sites tested. This was probably due to the difference in resistivity characteristics of the soil at these two sites. At ASA #615, the resistivity decreased with increasing depth below 4 feet. The 6-foot ground rod penetrated the higher resistivity soil near the surface and made contact with the lower resistivity soil below. Thus, it provided the most effective grounding performance of the other configurations.

The buried wire at ASA #615 showed the lowest resistance after driving over the furrow to better compact the soil to increase the wire surface area in good contact with the soil. Performance of the surface wire was also improved over 50 percent by the addition of water only.

At ASA #703, the ground rod showed a poorer performance as compared with the horizontal earth electrodes. This was probably due to the fact that the soil resistivity remained high, down to a 6-foot depth, the full length of the ground rod. The surface wire with ground pegs showed the lowest resistance before special enhancement techniques were used. The buried wire showed the lowest resistance at this location as well as at ASA #615, after walking over the furrow to improve the earth contact. The mats at this location performed well, because of the addition of 26 ground pegs, which increased the earth surface contact area.

Phase II Resistance Data Summary. Table 22 shows selected comparative resistance data for each earth-electrode configuration at all test sites. These data show that the horizontal grounding systems generally provided better performance than a vertical ground rod.

Table 22

Summary Baseline Data Comparisons (Resistance-ohms)

	APG(1)	APG(2)	Drum(3)	Bliss	Yakima	Lewis	Story	Huachuca(4)
Ground rod	46	248[b]	9,990[b]	62[b]	99	7,190[b]	13	39[b]
Mats	107[b]	135	7,490	19[a]	140[b]	1,270	110[b]	37
Surface wire	37[a]	61	135	39	35[a]	744[a]	4	17
Buried wire	38	36[a]	111[a]	23	129	986	2[a]	10[a]

Note. Numbers in parentheses designate specific areas. 1 = Old Airport; 2 = Building 799; 3 = Area 4C; 4 = ASA #703.

[a]Lowest value at each location.
[b]Highest value at each location.

One reason is that the surface area in contact with the soil for the horizontal systems tests larger than that of a single ground rod. For example, a 6-foot long, 3/4-inch-diameter ground rod has about 170 square inches of surface area in contact with the soil. The 100-foot surface wire with 26 ground pegs 6 inches long and a 1/2-inch-diameter has about 480 square inches of surface area in contact with the soil. This calculation is based on only half of the surface area of the wire being in contact with the soil. (This would suggest that covering the surface wire completely with soil--which would increase the total surface area contact to about 716 square inches--would significantly improve grounding performance above the values measured.) Thus, it would require nearly 3 ground rods to provide surface area equal to that of the 100-foot surface wire with ground pegs (480/170 - 2.82).

The second reason for the generally better performance of the horizontal earth electrodes is that the soil resistivity at most of the test sites increased or remained constant with increasing depth. It has been conventionally assumed that resistivity decreases with depth. Field tests have pointed out, however, that there is a wide variability in resistivity values and profiles at sites relatively close to one another. Where increasing resistivity with depth was found, the ground rod encountered higher resistivity soil as it was driven deeper, while the horizontal ground systems were in contact with lower resistivity soil at the surface. Where the resistivity remained constant with depth, the greater surface areas of the horizontal systems provided better grounding performance.

Human Factors Data

In addition to resistance and resistivity measurements, other data were collected that pertained to human factors involved in the use of various earth-electrode configurations. Installation and removal times for each of the test sites are in Table 23. The average installation and removal times, with some exceptions for ground rods at particularly difficult sites, showed no major differences for any of the grounding systems tested.

Table 23

Comparative Installation and Removal Times (minutes)

Test site	Ground rod Install	Ground rod Remove	Mats Install	Mats Remove	Surface wire Install	Surface wire Remove	Buried wire Install	Buried wire Remove
Old Airport APG, MD								
13 Nov 84	2	4	7	7	2	2	9	5
16 Nov 84	2	50[a]	10	b	4	b	4	b
28 Nov 84	1	1	7	3	3	2	3	2
Bldg. 799 APG, MD								
18 Jan 85	4	b	7	3	10	3	7	3
Phillips Army Airfield APG, MD								
8 Feb 85	2	4	5	2	5	3	15	4
Fort Drum, NY								
26 Feb 85, 12B	5	b	5	4	9	3	10	5
28 Feb 85, 12B	2	b	3	2	6	2	b	b
28 Feb 85, 4C	1	1	3	2	9	3	6	3
Fort Bliss, TX	3	1	3	4	4	2	5	2
Yakima F.C., WA	a	a	9	b	8	b	8	6
Fort Lewis, WA	23	4	4	3	6	6	18	3
Fort Story, VA	b	b	12	5	4	b	b	b
Fort Huachuca, AZ	9	4	17	2	9	3	20	3
Average time (minutes)	5	3	7	3	6	3	10	4

[a]Excessive times deleted from averages.
[b]Circumstances prohibited the collection of specific data.

Table 24 summarizes human factors data obtained during the testing. Two persons were always required to install a ground rod: one to hold the rod, the other to drive it into the ground with a sledge hammer. The mats and surface wire could be laid out by one person. However, it was more convenient to use two people, and the times shown in Table 23 are based on a two-person installation and removal. The buried wire always required at least two persons: one to drive the vehicle, while the other observed the action of the plow and directed the driver.

Table 24

Human Factors Data

Measurement	Rod	Mat	Surface wire	Buried wire
Number of personnel required to install/remove electrode	2	1	1	2
Average time to install (minutes)	5[a]	6	6	8
Average time to remove (minutes)	3[a]	4	3	4
Approximate weight (lb)	23[b]	8	18[c]	84
Approximate stored size (cu ft)	.04	6	1	12
Approximate stored dimensions (L + W + D in feet)	6	6	3	9

[a]Does not include some cases where excessive time was required; e.g., grounds rods in hard rocky soil: 30+ minutes.
[b]Includes ground rod and sledge hammer.
[c]Includes 26 ground pegs, 100 feet of cable and 3-lb hammer.

In terms of ease of installation and removal, the ground rod and the buried wire were the most difficult to use, as compared with the surface wire or the mats. At several sites it was difficult (it not impossible) to drive the ground rods into the soil. At such sites, when the ground rod was driven as far as possible into the soil, it was equally difficult (if not impossible) to remove the rod. Using the 10-pound sledge hammer accurately requires a good bit of skill. In some cases misplaced blows caused sledge hammer handles to crack and, in other cases, nearly caused serious injury to the person holding the rod. To minimize the chance of personal injury, the testers resorted to using jury-rigged support wires to steady ground rods.

The buried wire configuration was designed for connecting the plow to the bumper of a standard 2-1/2-ton Army truck. If this particular vehicle was not available, the plow could be adjusted to attach to other vehicles having different bumper heights. Such installation in some cases, however, resulted in its being bent when used in hard, rocky desert soil. Also, where there was no natural hollow in the soil in which to start the plowing action, it was necessary to dig out a starting hole.

The weight of the ground rod shown in Table 24, includes a 10-pound sledge hammer plus a single ground rod. (Normally, several ground rods must be carried during a tactical operation to ensure one is available in the event one is broken, damaged, or cannot be removed.) The weight of the surface wire in Table 24 includes a 3-pound hand-held hammer plus 26 ground pegs 6 inches long. The mats' weight includes two 6-foot by 8-foot mats, but does not include any ground pegs used for anchoring the mats. The major component of the buried wire weight is the plow.

Table 24 shows two storage indicators for each configuration: volume (cubic feet) and sum of lineal dimensions (stored dimensions). The dimensions used to estimate these storage factors are shown in Table 25.

Table 25

Earth-Electrode Storage Dimensions

Configuration	Lineal dimensions (feet) Length	Width	Diameter
Ground rod	6	1/12	1/12
Mats (folded)	3	2	1
Surface wire (spooled)	1	1	1
Buried wire	6	2	1

Note that while the volume of a single ground rod is the smallest, by far, the lineal storage indicator in Table 24 shows the spooled surface wire configuration to be the smallest. The lineal storage indicator provides a measure of the bulkiness of the stored package.

Phase III - Enhancement Techniques

Chemical Enhancement Techniques

To evaluate conventional chemical soil-enhancement techniques for reducing soil resistivity, tests were conducted at Yakima Firing Center on both vertical and horizontal systems.

Vertical systems. Figure 17 summarizes the results on enhancement techniques for vertical ground rods. It shows the variation in resistance of each configuration over time after the application of water and/or salt.

The resistance of the dry rod (#1) remained nearly constant throughout the 5 hours it was monitored. The slight increase in resistance probably was due to the cooling of the dry ground rod in the cold desert soil. This site was at an altitude of about 5,000 feet and air temperature was in the 50-degree Fahrenheit range.

Rod #2 showed a slight drop after the initial addition of water. The second application of water, about 1-1/2 hours later, caused about a 30 percent reduction in resistance with the water rapidly permeating the already wetted-down soil.

The open basin trench technique used on rod #3 showed immediate results, with nearly 80 percent reduction in resistance within only a few minutes after the application of salt water.

The doughnut trenching technique used on rod #4 was ineffective for the 5-hour test period. After 5 hours, the application of additional salt water into the doughnut trench did cause a 36 percent reduction in resistance. While this may be a less corrosive technique than the basin trench method used on rod #3, it takes a much longer time for the water to permeate the soil and make contact with the rod.

Horizontal systems. For the two horizontal ground wire systems tested, enhancement with water and salt caused immediate results. Figure 18, summarizing these results, shows a somewhat larger reduction in resistance for the buried wire than for the surface wire. This may have been due to the more immediate contact of the salt water with the buried wire, as compared with a longer time needed to permeate the soil to wet down the ground pegs of the surface wire.

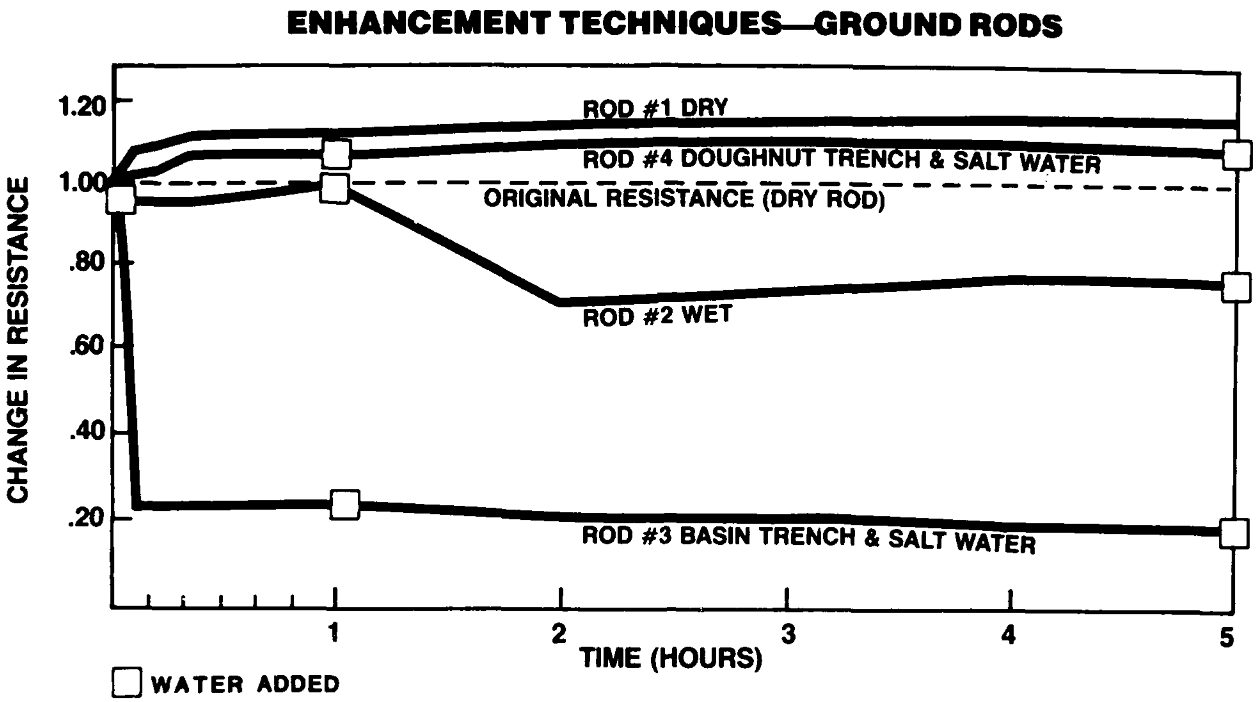

Figure 17. Ground rod enhancement data.

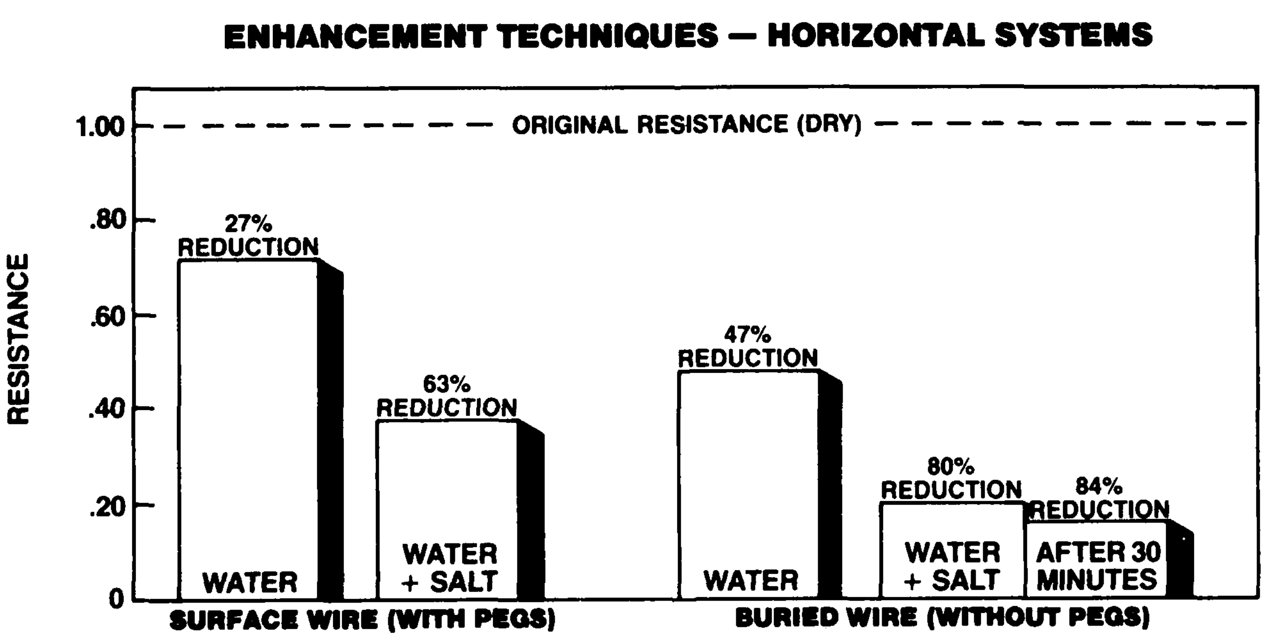

Figure 18. Horizontal systems enhancement data.

Multiple Electrode Enhancement Techniques

To evaluate the impact of the connecting electrodes together at sites where more than one CE facility exists in the immediate area, tests were conducted at Yakima Firing Center using two surface wire systems. The results are described in Table 26. There was only enough equipment available to actually install two surface wire systems. The impact of combining more than two was estimated using the formula for combined resistance of straight-parallel wires given by Sunde (1949). Note that as more grounding systems were combined (theoretically), performance increase tended to diminish. As a field expedient, the results of the multiple electrodes can be approximated using the formula

$$\underline{R}\ (\text{total}) = 1/(1/\underline{R}1 + 1/\underline{R}2 + \ldots\ 1/\underline{R}n), \qquad (1)$$

where $\underline{R}1$, $\underline{R}2$, and $\underline{R}n$ are the resistance values of each electrode.

Table 26

Multiple Electrode Enhancement Data

Earth electrode	Resistance (ohms)
First 100' surface wire with 26 ground pegs-alone	563
Second 100' surface wire with 26 ground pegs-alone	311
Two surface wire systems-connected	214
Three surface wire systems-connected[a]	170
Four surface wire systems-connected[a]	134
Five surface wire systems-connected[a]	111
Six surface wire systems-connected[a]	95
Seven surface wire systems-connected[a]	84
Eight surface wire systems-connected[a]	75

[a]Values shown are theoretical.

SUMMARY AND CONCLUSIONS

This project represents an exploratory analysis and limited testing program of conventional and alternative grounding systems for tactical CE equipment. The conclusions and recommendations are based on measurements at selected field sites and are valid only for those particular sites. They are intended, however, to be representative of a wider range of soil types, weather, and climatic conditions.

The conclusions of this study are summarized as follows:

- The surface wire with ground pegs generally gave resistance values from 20 to 90 percent lower than the ground rod at the same sites.

    a. This configuration was easier and safer to install and remove.

    b. It can be visually inspected for soundness after installation.

    c. It is adaptable for installation in all types of soil.

    d. It can be stored compactly and easily handled in transit.

- The buried wire generally gave superior performance to the ground rod when firmly embedded in the soil. It does have the highest system weight, however. Storage and handling factors are also more burdensome than with the ground rod.

- The mats' grounding performance varied widely depending on the degree of contact with the soil. It was difficult to make good contact over grass, rocks, and rough terrain.

- The null-balance earth tester (Megger®) was found to be a valuable tool for measuring grounding system resistance and earth resistivity. It provides a means for prospecting for good grounding sites and selecting the best type of grounding configuration to use at a particular site. It is simple to use and the procedures are easily learned. At selected sites, local enlisted personnel installed the grounding systems and carried out the resistance and resistivity measurements. They were easily able to follow the installation and instrumentation procedures and used the null-balance earth tester after only a few minutes of instruction.

RECOMMENDATIONS

Based on the conclusions we recommend that:

- the Army use surface wire with ground pegs as a superior alternative to ground rods for grounding tactical mobile CE equipment.

- the Army use a null-balance earth tester for prospecting grounding sites and measuring grounding system performance.

- the Army publish a revised guidance document on grounding practices, including the use of horizontal earth-electrode systems such as the surface wire with ground pegs and the use of a null-balance earth tester.

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APPENDIX A

TECHNICAL BACKGROUND

TECHNICAL BACKGROUND

Effective grounding of tactical CE equipment is necessary for three basic reasons: personal safety, equipment and facility protection, and reduction of electrical noise.

Personal safety can be ensured by providing a low impedance path for currents, due to electrical faults, to be shunted to the ground and away from people. Ground wires are sometimes used throughout the power distribution system to conduct fault currents to fuses or circuit breakers. Bonding between equipment, metallic objects, piping and other conductive objects, and the ground are also used to eliminate shock hazards.

Equipment and facility protection are obtained by using circuit breakers and fuses. They interrupt the flow of electrical current before it can damage equipment. Protecting a facility from lightning can be provided by installing lightning rods to divert the discharge and conduct it to the ground. Tactical units in the field, however, do not use lightning rods.

Electrical noise on communications circuits can be reduced by providing a low impedance ground path between signal ground point connections throughout the communications systems, by bonding between equipment, and by shielding noise sources. A good ground path provides a sink to drain off electrical noise that otherwise would degrade communications signals. A common signal reference ground can be provided by using a bus bar or other conductor within a piece of equipment.

All of these types of grounding systems require a connection to an earth electrode to conduct electrical current to the ground potential. The earth electrode makes direct contact with the earth and is the key element terminating all grounding systems.

The basic measure of effectiveness of an earth electrode is the resistance, in ohms, to the flow of electrical current into the surrounding earth. Grounding resistance requirements for CE facilities are outlined in several Army documents. One in particular, MIL-STD-188-124 (DoD, June 1978), clearly describes the use of driven ground rods as a satisfactory earth-electrode subsystem. It also indicates that where a 10-ohm resistance to earth of the ground rod is not obtained, alternative methods should be considered.

Resistance to the flow of electrical current through an earth electrode has three components:

1. Resistance of the electrode itself and connections to it.

2. Contact resistance between the electrode and the soil adjacent to it.

3. Resistance of the surrounding earth.

Most earth-electrode designs (rods, pipes, underground metal objects, etc.) have sufficient size and mass so their inherent resistance is a negligible component of the total resistance.

Contact resistance generally has a greater impact on the total resistance, but it is not significant if the electrode is free from paint, grease, or other surface insulators. The Bureau of Standards has shown that contact resistance is negligible if the earth is firmly packed around the earth electrode.

Generally, the resistance of the surrounding earth will be the largest of the three components making up the total resistance of an earth electrode. Electrical current flows radially outward from the surface of the ground rod in all directions. It can be conceptualized as flowing through equipotential hemispherical shells concentric to the ground rod and perpendicular to the radial flow of current. As the constant amount of current flows from the ground rod, its density will decrease with distance away from the ground rod. This is because the areas of the successive shells become larger and larger with distance from the ground rod. The earth shell nearest the electrode naturally has the smallest surface area and so offers the largest resistance. As the distance away from the electrode increases, the inclusion of additional earth shells does not add significantly to the total resistance of the earth surrounding the electrode. This area of influence of an earth electrode extends in all directions away from the rod, theoretically to infinity, with less and less influence as the distance increases.

Factors Affecting Grounding

There are two basic factors affecting grounding: the soil characteristics and the physical configuration of the earth-electrode system.

Soil Characteristics

Electrical current flows through the earth primarily as ion movement, that is, by the movement of electrically charged atoms, groups of atoms, or molecules. This ionic conduction depends, to a great extent, on the concentration of salts and the kinds of salts in the soil. When these salts dissolve, the ions separate from the salt molecules. It is the movement of these ions under the influence of an electrical potential that allows the soil to conduct electricity. And it is the resistance of the soil to this movement of ions that determines the resistance of the grounding electrode to the flow of electricity into the earth.

Every ground site has its own specific resistance to the flow of electrical current. This characteristic of the soil is called its resistivity. Resistivity is defined as the electrical resistance of a cube of homogeneous material (see Figure A-1). It is directly proportional to the length of one side of the cube, and inversely proportional to the area of one face of the cube. This means the resistance increases as the length of material through which the electrical current must flow increases, and it decreases as the size of the square "tube" of earth through which the electrical current flows increases. This relationship takes the form

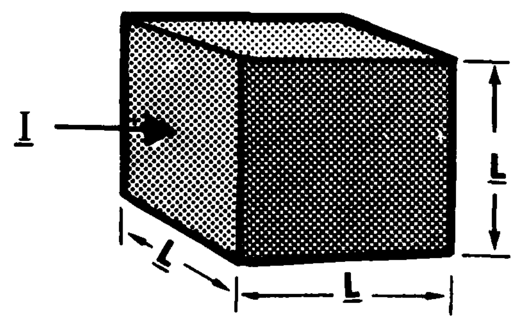
$$\rho \text{ is proportional to } \underline{L}/\underline{L}^2 \tag{2}$$

because the face area varies as the square of the length of one side of the cube, the resistance of the cube will decrease in direct proportion to the increase in the length of the side of the cube, or generally speaking, to the increase in the size of the cube. This can be expressed as

$$\underline{R} \text{ (resistance) is proportional to } {}^{1}/\underline{L}. \tag{3}$$

$\underline{L}$ is length and the area equals the length squared ($\underline{A}=\underline{L}^2$). Not surprisingly, this means that the more earth the electrode can connect with, the lower the resistance will be to a given electrical potential. The greater the volume of earth in which to dissipate the electrical charge, the lower the resistance will be to that charge. Soil resistivity ρ is usually expressed in terms of ohm-centimeters. It can also be expressed in ohm-meters or ohm-feet. Expressed in this way, it is independent of the size of the cube of earth. For example, if the cube is doubled in size, the resistance will be halved, and resistivity in ohm-cm will remain constant for that particular homogeneous soil.

SOIL RESISTIVITY (ρ)
RESISTANCE OF SOIL ITSELF TO FLOW OF ELECTRICAL CURRENT ($\underline{I}$)



ρ IS ELECTRICAL RESISTANCE OF A CUBE OF HOMOGENEOUS MATERIAL, EXPRESSED IN OHM-CENTIMETERS

Figure A-1. Soil resistivity.

Soil resistivity can vary widely among grounding sites, even when they are in close proximity to one another. This characteristic is affected by the type of soil, by its moisture and dissolved salt content, by temperature, and by seasonal changes. Table A-1 provides an indication of the order of magnitude values to be expected from different types of soil. The variation of resistivity of a given type of soil with moisture, temperature, and salt concentration is shown in Figure A-2. These curves indicate trends only, and will vary in specific values from one type of soil to another. Note that resistivity goes down with increasing moisture, temperature, and salt concentration. As shown in the temperature curve, there is a discontinuity in resistivity at the freezing point, with a marked increase in resistivity with decreasing temperature below freezing.

Table A-1

Soil Resistivity Variation[a]

Type of soil	Resistivity (ohm-cm)
Wet organic soil	10^3
Moist soil	10^4
Dry soil	10^5
Bedrock	10^6

[a]Reference MIL-HDBK-419 (DoD, 1982).

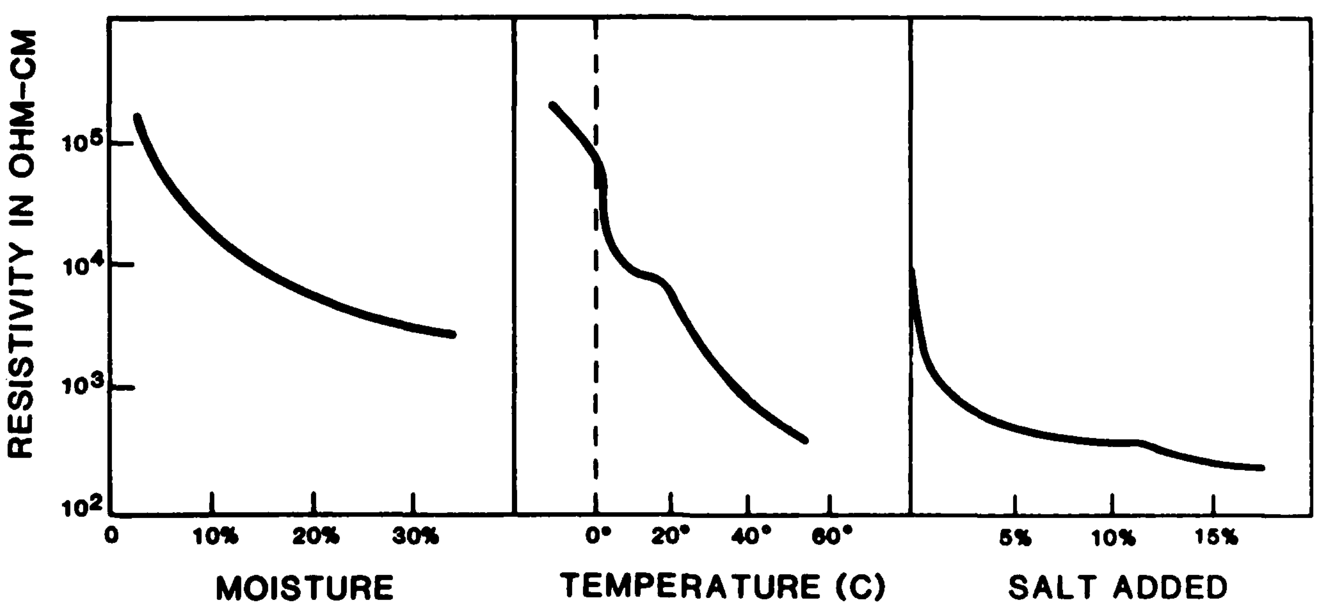


Figure A-2. Soil resistivity variation.

Physical Configuration

The second factor affecting grounding effectiveness is the design of the earth-electrode system, its physical configuration. Grounding system configurations can be categorized into two basic types: vertical and horizontal. Vertically driven ground rods, or pipes, are the most common type of vertical systems. They may be used individually or in groups that are electrically connected. In some areas steel pipe used for casing the wells can be used as a ground electrode.

When bedrock is near the surface, or when vertical rods cannot be driven into the ground, horizontal ground systems are used. Such systems may also be more effective when the ground resistivity increases with increasing depth below the surface. Such systems may be horizontal strips of metal, solid wire, stranded cables, flat metallic plates, or grids buried in the soil.

In many cases, hybrid grounding systems consisting of combinations of these two basic types are used. Metal frameworks of buildings may be suitable, depending on the size of the building, the type of footing, and the type of subsoil at the particular locations. Towers or buildings resting on steel pilings usually will exhibit low resistance and can be used. Metal underground waterpipes have been traditionally used for grounding. Water pipes alone, however, should not be relied on because they sometimes may be disconnected for repairs or may have nonconductive couplings inserted. In typical field operations, however, such in-place metallic objects may not be available, and other types of earth electrodes that are more easily handled, stored, and removed must be used.

In developing a suitable design for an earth electrode, there are several factors that must be considered. First, as discussed previously, the more earth an electrode can connect with, the lower the resistance will be. Thus, increasing the length and diameter of a vertical or horizontal earth electrode will generally improve the effectiveness of the grounding. Figures A-3 and A-4 show the changes in resistance that occur with rod length and rod diameter. It is evident that length has a much greater impact on lowering resistance than the diameter.

EARTH-ELECTRODE RESISTANCE VARIATION

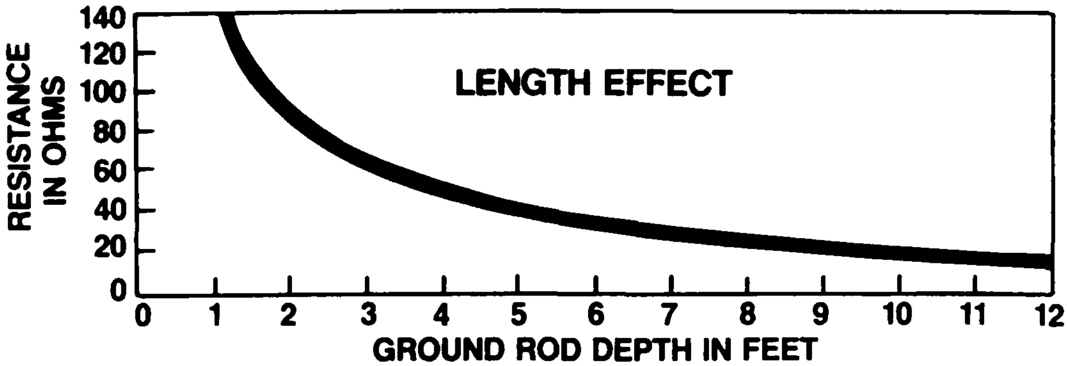


Figure A-3. Effect of rod length on resistance.

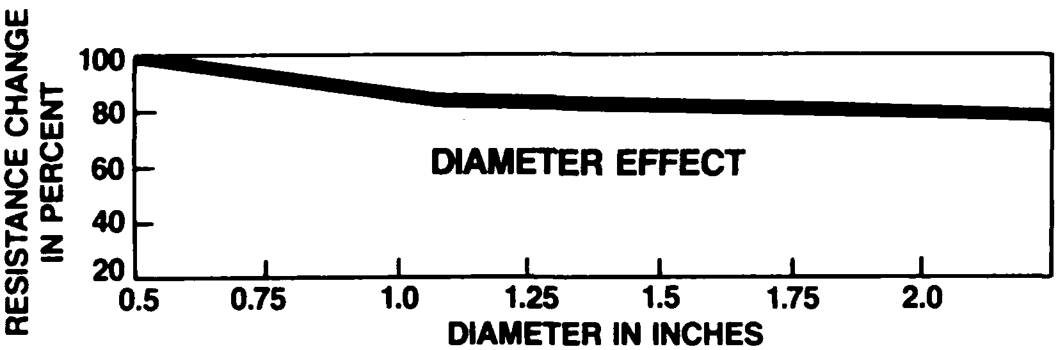


Figure A-4. Effect of rod diameter on resistance.

The use of multiple rods or horizontal electrodes can provide a lower resistance grounding system. When multiple rods are used, their spacing will be an important factor affecting grounding system performance. Based on theoretical distribution of electrical current in perfectly homogeneous soil, it can be shown that about 85 percent of the total resistance to earth of a 10-foot ground rod is established within a 10-foot radius of the rod (see Figure A-5). Doubling the radius to 20 feet only increases the percentage of the total resistance to earth to 92 percent. One hundred percent resistance is theoretically achieved only at an infinite distance away from the rod.

NATURE OF EARTH-ELECTRODE RESISTANCE

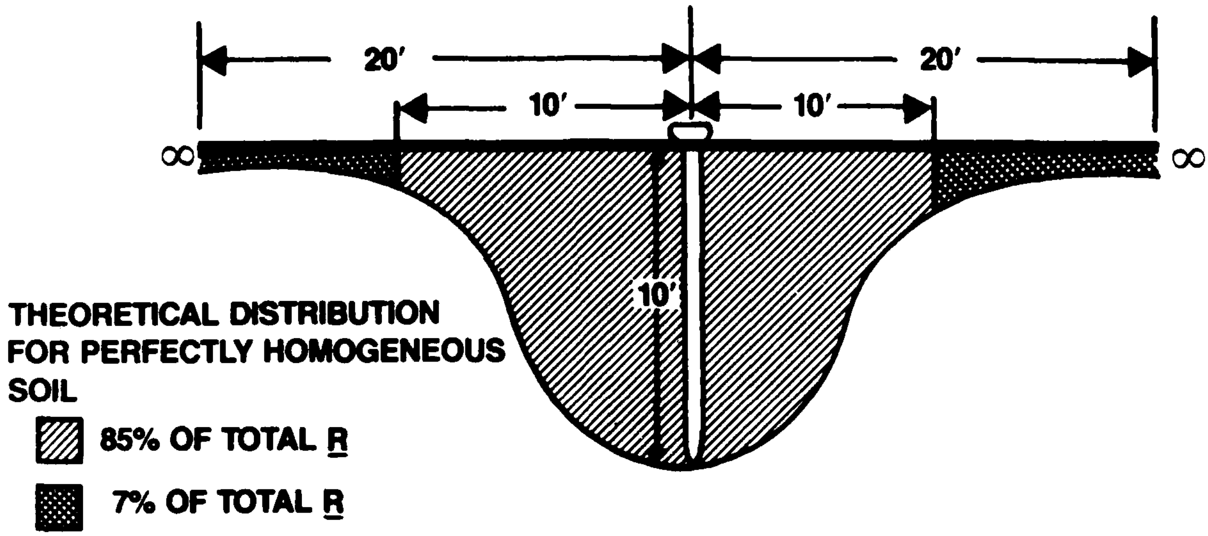


Figure A-5. Distribution of rod to earth resistance.

Thus, it can be seen that most of the resistance of a single rod is obtained within one or two rod lengths (85 percent at one rod length; 92 percent at two rod lengths). If electrodes are too closely spaced, the total effectiveness of each one will not be realized. Because of overlap of their areas of influence (see Figure A-6), less earth will be available for absorbing the current from each electrode. This prevents the resistance of N identical electrodes connected in parallel from being 1/N times the resistance of one of the electrodes. Therefore, the crowding of multiple vertical rods is not as beneficial, in terms of number of rods per ohm reduction, as using fewer rods properly spaced. As a general rule of thumb, the separation between vertical ground rods in a group of rods should be at least equal to or greater than twice the length of an individual rod.

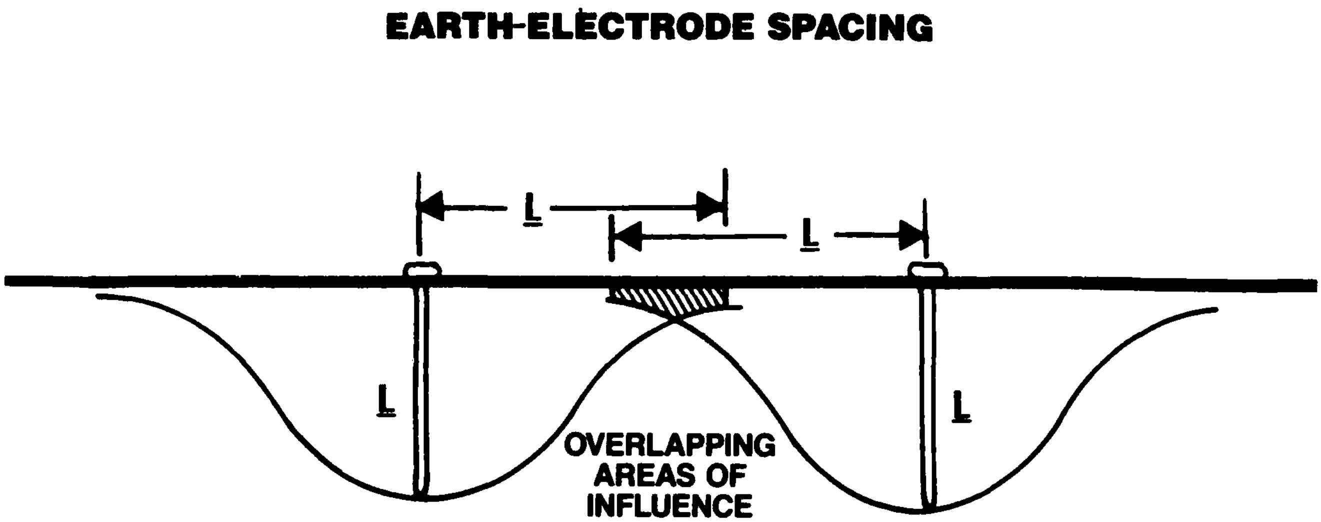


Figure A-6. Earth-electrode spacing.

APPENDIX B

ADDITIONAL RESISTANCE AND RESISTIVITY TEST DATA

Table B-1

Mats, Ground Pegs, and Weights Data,
Building 459, APG, Maryland (17 April 84)

Earth electrode	Resistance (ohms)
2 ea. 6' x 8' mats, 4+4, 4	69
2 ea. 6' x 8' mats, 4+4, 6	59
2 ea. 6' x 8' mats, 4+4, 8	53
2 ea. 6' x 8' mats, 4+4, 10	50
2 ea. 6' x 8' mats, 4+4, 10, 2+2 sandbags[a]	41
2 ea. 6' x 8' mats, 4+4, 10, 4+4 sandbags	40
2 ea. 6' x 8' mats, 4+4, 10, 6+6 sandbags	39
2 ea. 6' x 8' mats, 4+4, 12, 6+6 sandbags	39
2 ea. 6' x 8' mats, 8+8, 2	60
2 ea. 6' x 8' mats, 8+8, 4	45
2 ea. 6' x 8' mats, 8+8, 6	38
2 ea. 6' x 8' mats, 8+8, 8	34
2 ea. 6' x 8' mats, 8+8, 10	32
2 ea. 6' x 8' mats, 8+8, 10, 4+4 cement blocks	32
2 ea. 6' x 8' mats, 8+8, 10, 6+6 sandbags and 4+4 cement blocks	31
2 ea. 6' x 8' mats, 8+8, 2, 6+6 sandbags and 4+4 cement blocks	43

[a]This notation means that in addition to the ground pegs, 2 sandbags were placed on top of each mat.

Table B-2

Mats Outline, Pegs, and Separation Data, Building 459, APG, Maryland

Earth electrode	Resistance (ohms) Separation: 1'	10'	20'
2 ea. 6' x 8' outline, 12+12, 2	50	50	45
2 ea. 6' x 8' outline, 12+12, 4	39	37	35
2 ea. 6' x 8' outline, 12+12, 6	35	32	30
2 ea. 6' x 8' outline, 12+12, 8	32	29	27
2 ea. 6' x 8' outline, 12+12, 10	30	27	25

Table B-3

Mats Outline and Ground Pegs Data, Building 459, APG, Maryland

Earth electrode: 3/4 copper braid mat outline			Resistance (ohms)	
				18 Apr 84
2 ea. 6' x 8' outline, 8+8,	2	(50' sep)		40
2 ea. 6' x 8' outline, 8+8,	4	(50' sep)		35
2 ea. 6' x 8' outline, 8+8,	5	(50' sep)		33
2 ea. 6' x 8' outline, 8+8,	6	(50' sep)		31
2 ea. 6' x 8' outline, 8+8,	10	(50' sep)		30
2 ea. 6' x 8' mats, 8+8,	10	(50' sep)		48
			18 Apr 84	19 Apr 84
2 ea. 6' x 8' outline, 12+12,	2	(50' sep)	42	45
2 ea. 6' x 8' outline, 12+12,	4	(50' sep)	34	35
2 ea. 6' x 8' outline, 12+12,	6	(50' sep)	31	31
2 ea. 6' x 8' outline, 12+12,	8	(50' sep)	a	29
2 ea. 6' x 8' outline, 12+12,	10	(50' sep)	a	27
2 ea. 6' x 8' outline, 12+12,	12	(32' sep)	a	23
2 ea. 6' x 8' mats, 12+12,	12	(32' sep)	a	23
2 ea. 6' x 8' mats, 12+12,	12,	4+4 sandbags	a	23

[a]Circumstances prohibited collection of specific data.

Table B-4

Resistivity Methodology Data, Building 459, APG, Maryland (20 June 85)

Depth (feet)	ρ (ohm-cm) Normal probes, 18" brass rods	ρ (ohm-cm) Probes insulated, except bottom 1/2-inch
2	29,874	27,116
4	45,423	44,045
6	57,105	55,497
8	69,859	68,634
10	75,451	81,005

Table B-5

Ground Peg Spacing Data, Building 459, APG, Maryland (15 August 85)

Number of 6" ground pegs	Separation (inches)	Surface wire length	Resistance (ohms)
31	6	15'0"	89.9
31	12	30'7"	59.6
31	18	46'6"	47.5
31	24	60'6"	45.2

Table B-6

Ground Rod, Mats, and Buried Wire Data
Building 799, APG, Maryland (5 June 84)

Earth electrode	Resistance (ohms)
6' ground rod	189
2 ea. 6' x 8' mats	999
2 ea. 6' x 8' mats, no pegs, 6+6 sandbags	74
2 ea. 6' x 8' mats, 4+4, 6, no sandbags	50
2 ea. 6' x 8' mats, 4+4, 6, 6+6 sandbags	45
30' buried wire, 2-3" depth	94

Table B-7

Buried Wire Versus Ground Rod Data, Building 799, APG, Maryland

Date	Resistance (ohms)	
	Ground rod	Buried wire
18 May 84	210	116
22 May 84	203	117
24 May 84	196	95
29 May 84	181	70
31 May 84	171	79
1 June 84	178	81

Note. 6' ground rod driven to a depth of 5'. Rod is close to center of buried wire.
30' buried wire, 1/8" stranded steel cable, 2-3 inches deep.

Table B-8

Enhancement Data (Vertical Rods), Yakima Firing Center, Washington

Time	Resistance (ohms) Dry Rod 1	Water Rod 2	Basin Rod 3	Doughnut Rod 4
0955[a]	99	159	199[b]	137
1000	---	Water applied 2, 3, & 4		
1002		156		
1004	106			
1007			37.5	
1008				139
1009		156		
1011	106			
1013			37.3	
1014				143
1016		156		
1018	108			
1020			37.4	
1021				147
1022		157		
1023	109			
1024			37.3	
1025				148
1026		160		
1027	109			
1028			37.2	
1030				150
1031		160		
1032	109			
1033			37.2	
1034				152
1035		162		
1036	110			
1037			37.2	
1038				147
1040		162		
1101	109			
1102			37.2	
1103				143
1104		161		
1112				146
1113			37.4	
1115	111			
1127	111			
1128			37.2	
1129				148
1130		162		
1137	---	Water applied 2, 3, & 4		
1144	112			
1146			33.7	149
1147		116		
1148	113			
1149			33.0	
1151				149
1153		110		
1200		113		
1201	112			
1202			31.9	
1203				149
1223		113		
1224	114			
1225			31.4	
1226				147
1228		113		
1258	113			
1259			31.1	
1300				150
1301		115		
1332	117			
1334			31.0	
1335				150
1336		118		
1452	117			
1453			30.8	
1454				149
1455	---	Water applied 2, 3, & 4		
1501		95		
1503	117			
1505			30.0	
1507				100
1508		99		
1510	117			
1511			29.9	
1513				99.5

[a]Dry values for all 4 rods initially measured.
[b]Initial measurement made with basin trench empty, so that only 5' of rod was in soil. It was estimated that dry resistance measurement would have been 167 ohms if all 6 feet had been in contact with earth. This value was used for calculating percentage reduction of resistance (see Figure 17).

Table B-9

Resistivity Profile, Cherry Hill, Fort Lewis, Washington (22 May 85)

Depth (feet)	(ohm-cm) Location A	Perpendicular to Location A
2	344,338	238,609
4	493,333	331,678
6	612,417	442,365
8	612,837	a
10	553,648	a
12	558,447	a

[a]Circumstances prohibited collection of specific data.